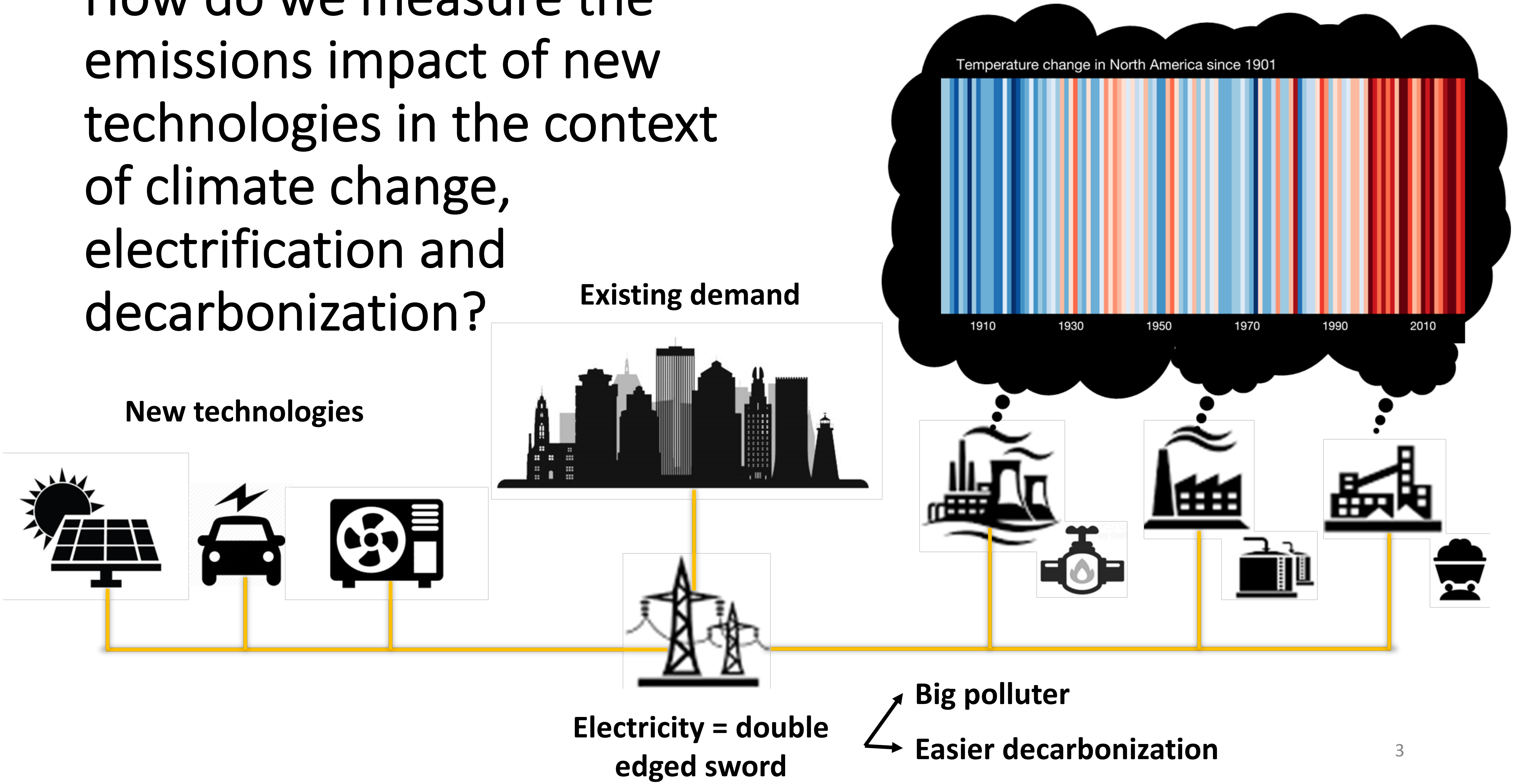
Emissions changes of adding technologies to the grid

Alejandro Elenes

Why this research topic?

- Where does electricity come from?
- Which power plants must be on, for us to get electricity?
- What are the rates of pollution and waste of these power plants?
- What would happen if I decide to change my behavior?
  - if I replace my car with an electric vehicle?
  - If I install solar panels in my rooftop?
  - if I replace my furnace with a heat pump?

How do we measure the emissions impact of new technologies in the context of climate change, electrification and decarbonization?



1) Start with the current grid

D_t

Vector with hourly data on electricity demand

$E(D_t)$

Vector with hourly data on grid emissions

2) Add new technology to grid

$$D_t$$

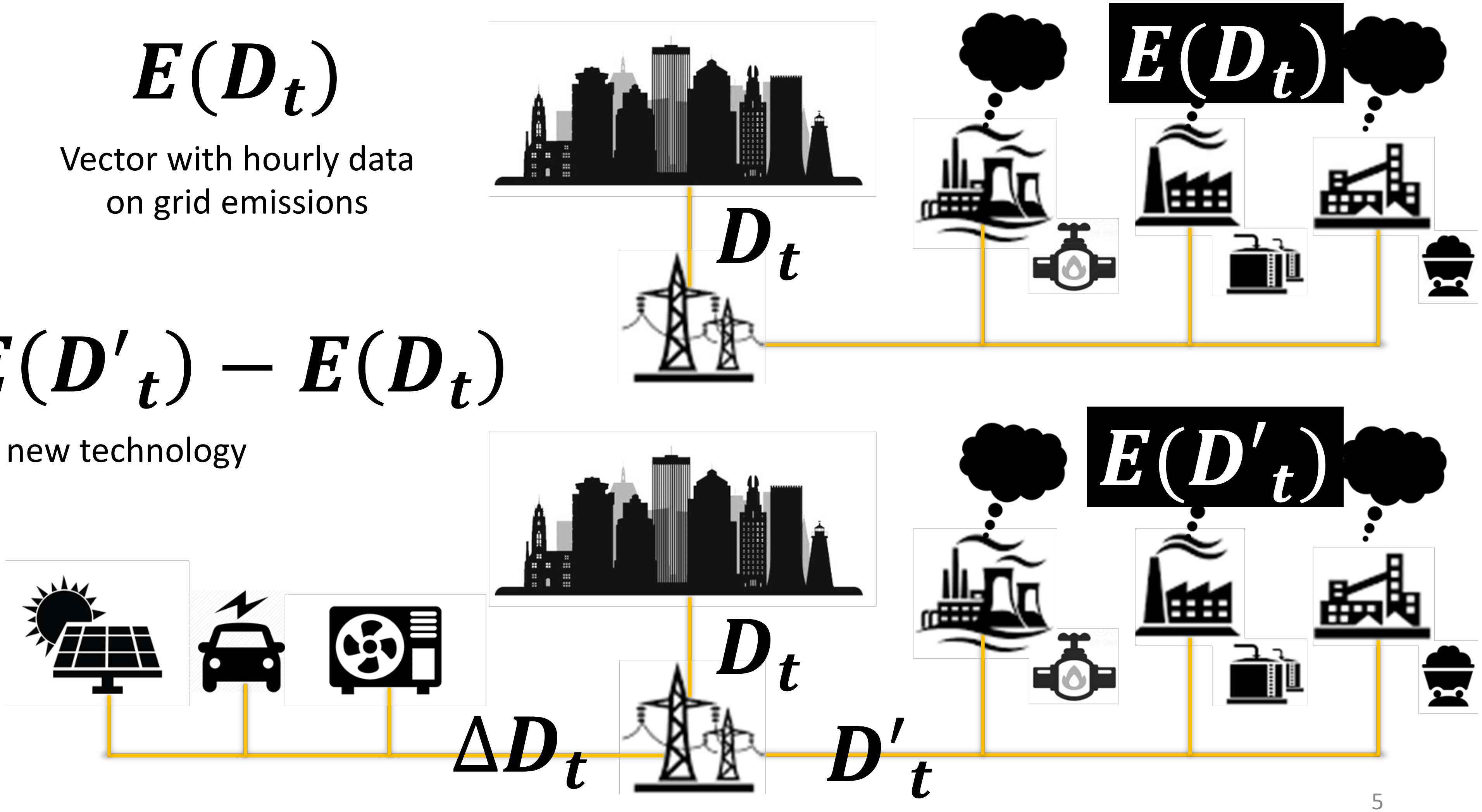
Vector with hourly data on electricity demand

$$E(D_t)$$

Vector with hourly data on grid emissions

$$E(\Delta D_t) = E(D'_t) - E(D_t)$$

Emissions of new technology



2) Add new technology to grid

$$D_t$$

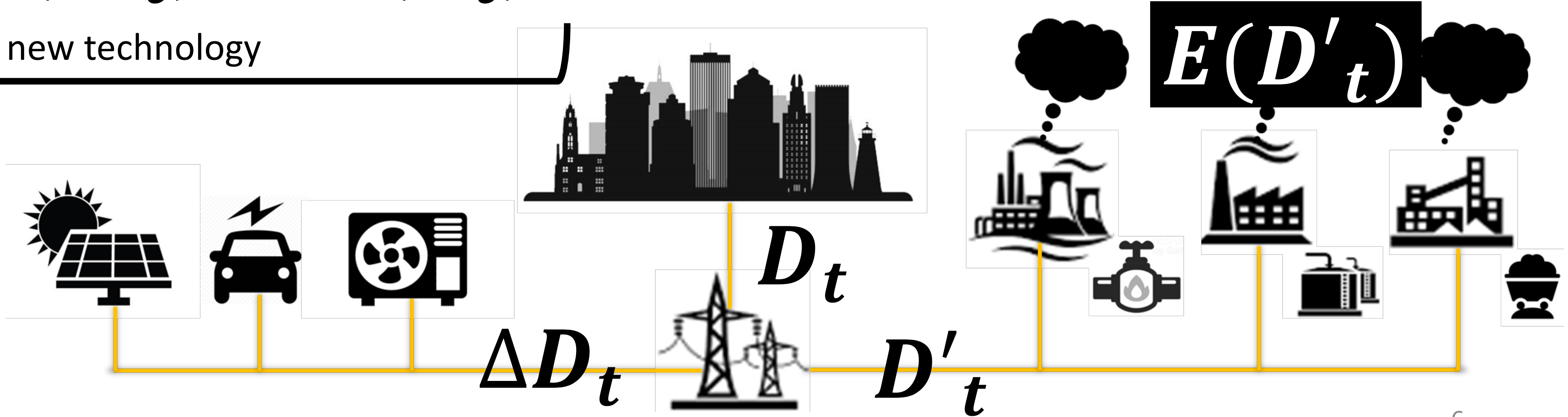
Vector with hourly data on electricity demand

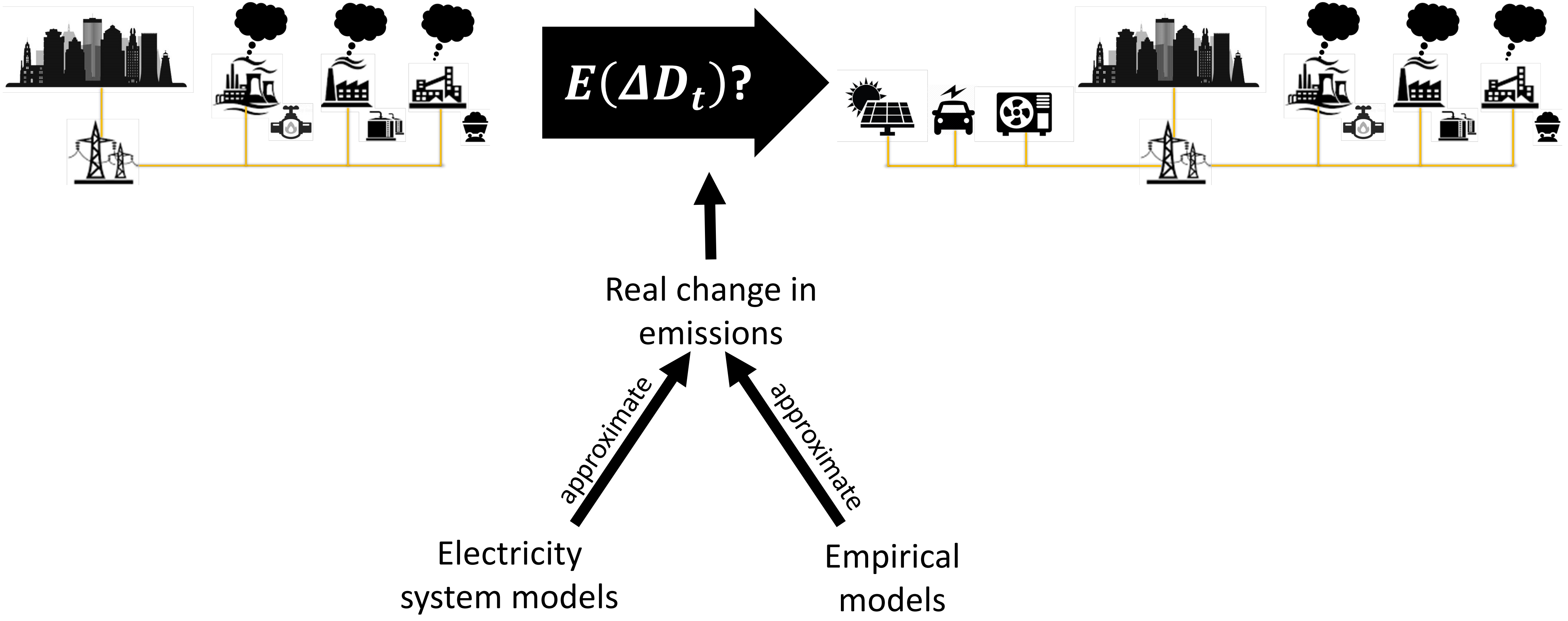
$$E(D_t)$$

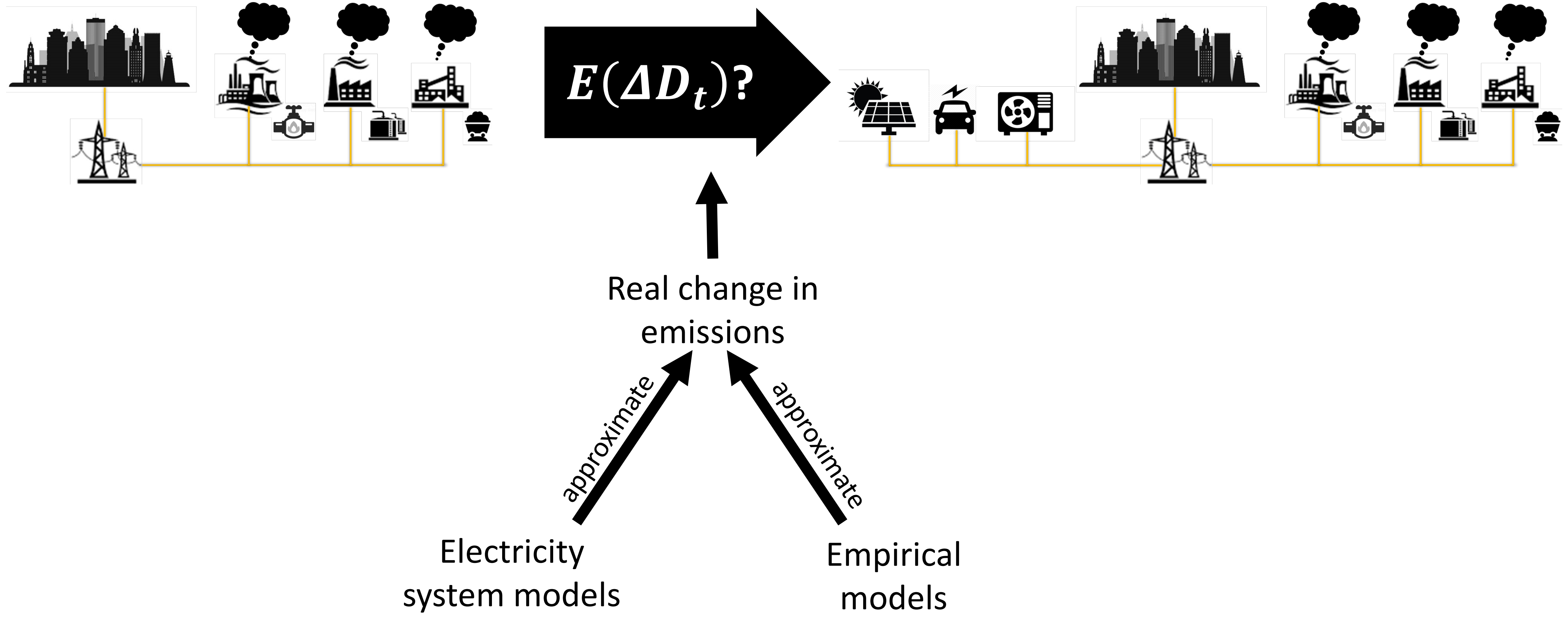
Vector with hourly data on grid emissions

$$\underbrace{E(\Delta D_t) = E(D'_t) - E(D_t)}_{\text{Emissions of new technology}}$$

Directly unobservable. We can't empirically observe grid operation with just one technology added.




$E(\Delta D_t)$?
Real change in emissions
approximate
approximate
Electricity system models
Empirical models



D_t

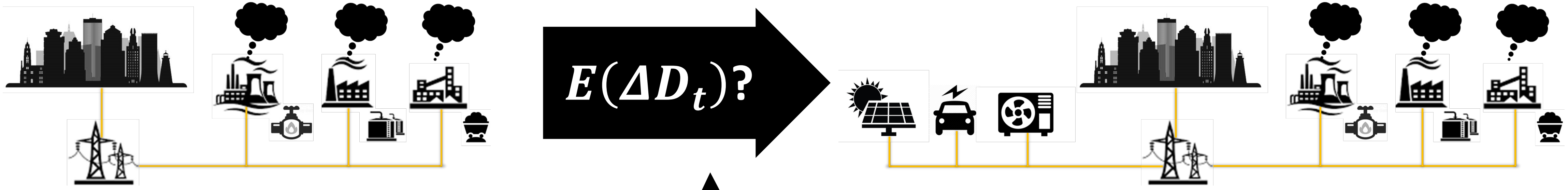
Vector with hourly data on electricity demand

$E(D_t)$

Vector with hourly data on grid emissions

$$E(\Delta D_t) = E(D'_t) - E(D_t)$$

Emissions of new technology



Real change in emissions

approximate

approximate

Electricity system models

Empirical models

$$D_t$$

Vector with hourly data on electricity demand

$$E(D_t)$$

Vector with hourly data on grid emissions

$$E(\Delta D_t) = E(D'_t) - E(D_t)$$

Emissions of new technology

$$\Delta D_t$$

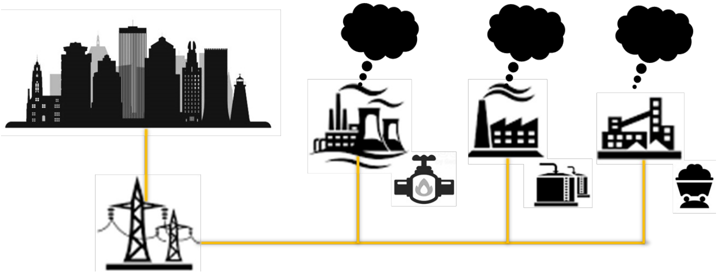
Vector with hourly data on change in electricity demand

$$MEF_t$$

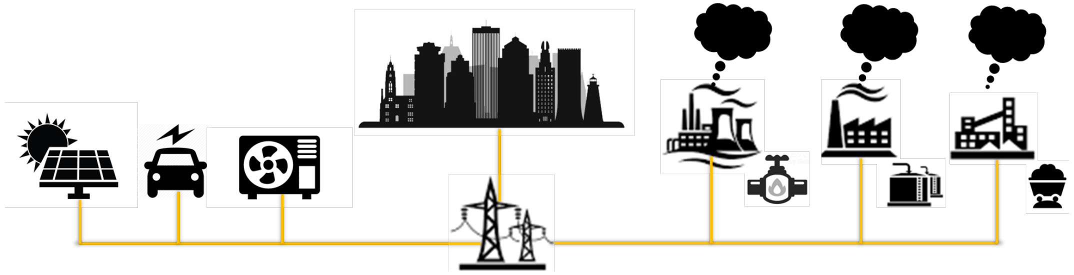
Vector with hourly data on marginal changes in emissions due to marginal changes in demand

$$E(\Delta D_t) = \Delta D_t * MEF_t$$

Approximated emissions of new technology



$$E(\Delta D_t)?$$



Real change in emissions

approximate

approximate

Electricity system models

Empirical models

This research: Can empirical approximate the simulation?

$$D_t$$

Vector with hourly data on electricity demand

$$E(D_t)$$

Vector with hourly data on grid emissions

$$E(\Delta D_t) = E(D'_t) - E(D_t)$$

Emissions of new technology

$$\Delta D_t$$

Vector with hourly data on change in electricity demand

$$MEF_t$$

Vector with hourly data on marginal changes in emissions due to marginal changes in demand

$$E(\Delta D_t) = \Delta D_t * MEF_t$$

Approximated emissions of new technology

How does the power grid work?

- Right now, we are consuming electricity in this building;
  How do we know what power plants to turn on first?
  - We operate whatever is cheaper first

- I buy a Tesla → emissions of charging it at GIS?
  - The grid will turn on the cheapest plant available

- The cost of plants dispatched changes smoothly, but emissions don't

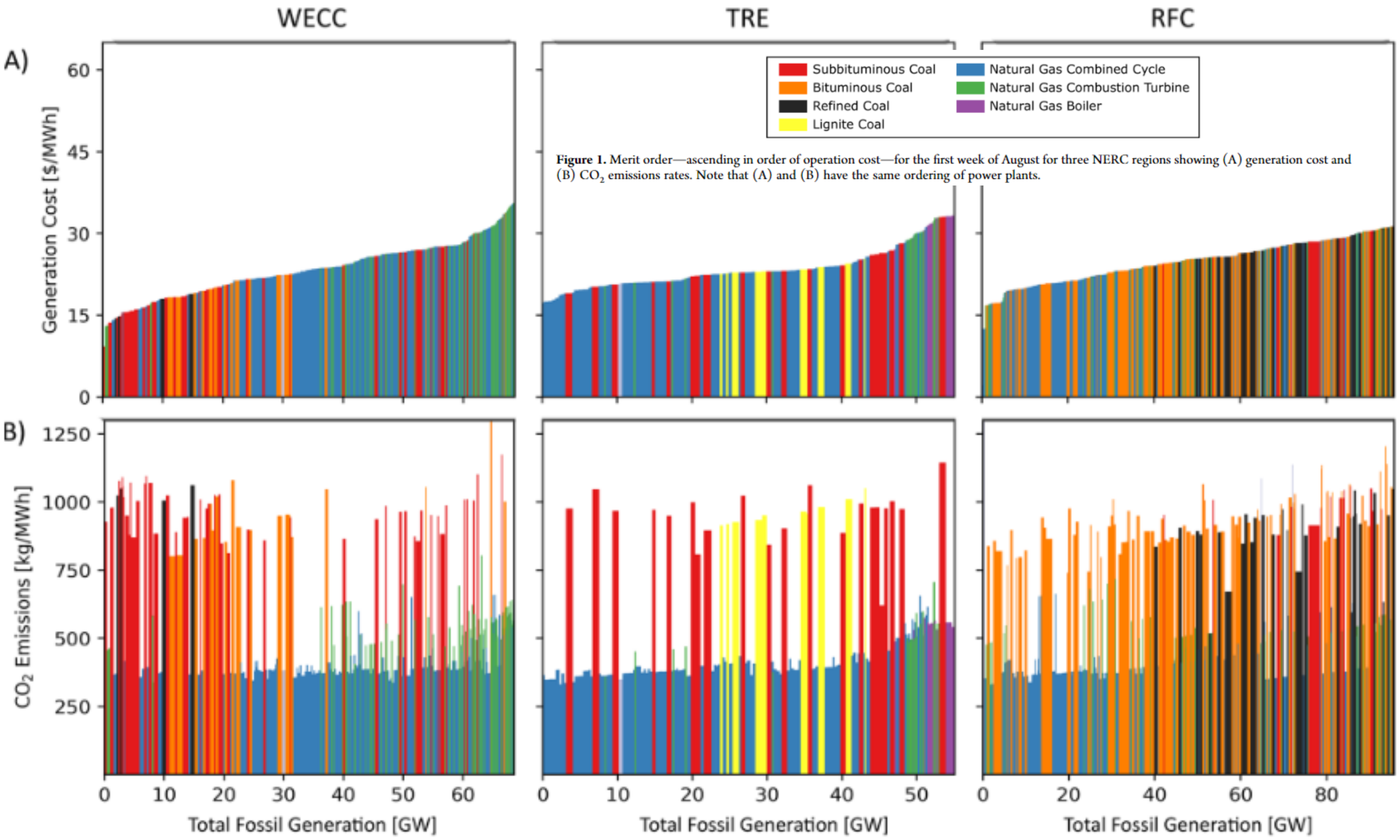


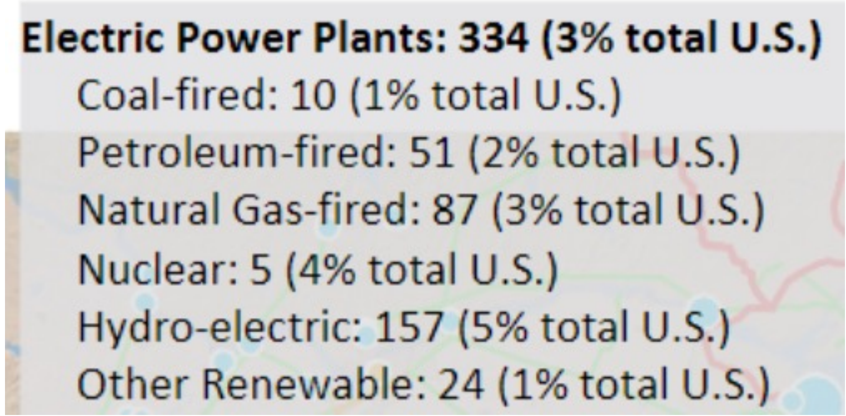
Figure 1. Merit order—ascending in order of operation cost—for the first week of August for three NERC regions showing (A) generation cost and (B) CO_2 emissions rates. Note that (A) and (B) have the same ordering of power plants.

Where do emissions come from?

- The power grid does not change every day
- The plant we had 1 week ago, 1 year ago, we still have them (likely)
- We can look at data from 1-2 years ago, check what plants were running back then to get a sense of where do emissions come from
- So, let's do that:
  - Google eGRID or go to link Emissions & Generation Resource Integrated Database (eGRID) | US EPA
  - Click on 'Explore the Data'

Explore eGRID data

- Output emissions rates: all emissions divided by all generation
- New York Upstate is 234 lb/MWh
- The lowest emission rate of the country?
  - I kind of want to see what power plants NY has
    - 334 power plants
    - Nuclear, gas, hydro → a very clean grid

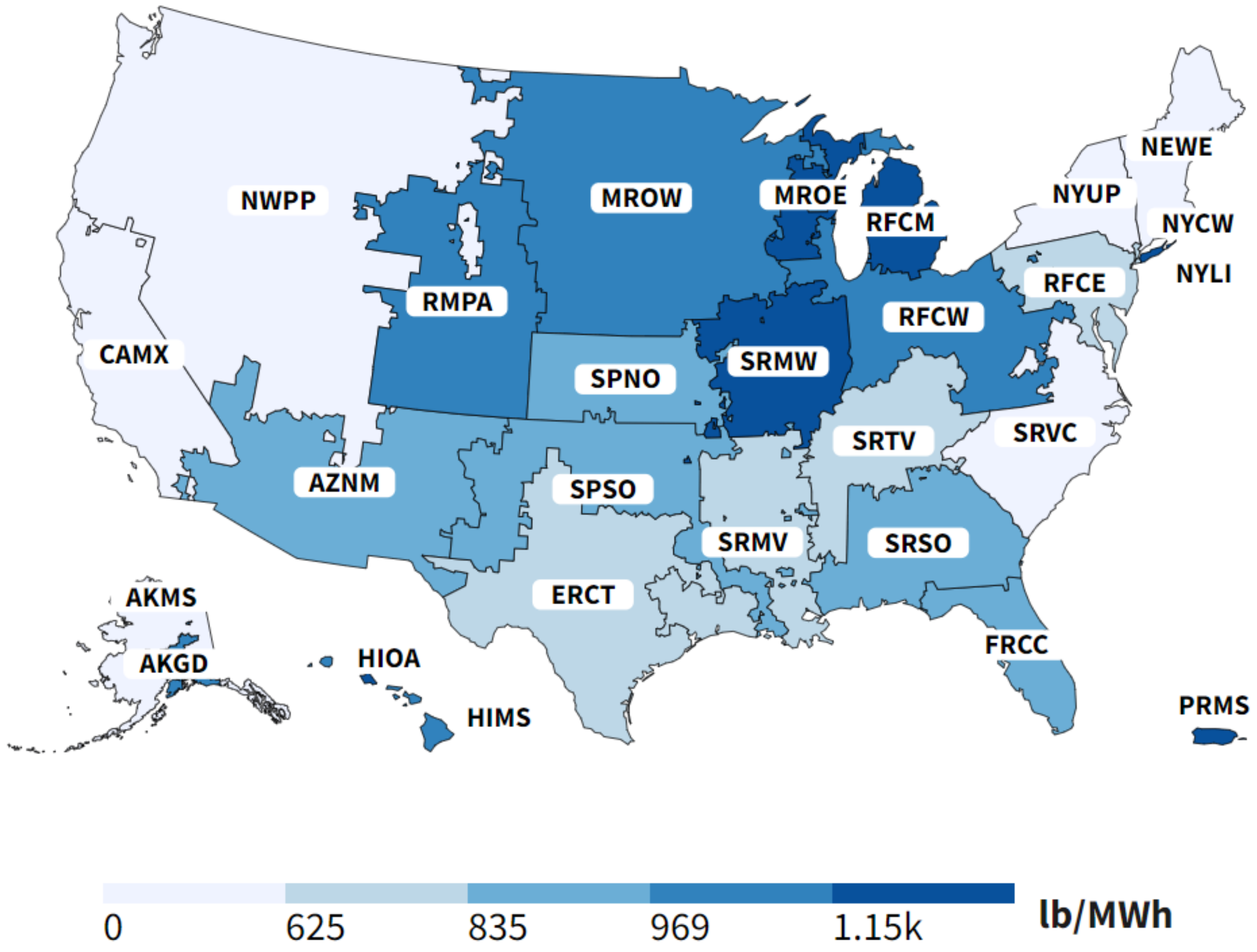


Electric Power Plants: 334 (3% total U.S.)
Coal-fired: 10 (1% total U.S.)
Petroleum-fired: 51 (2% total U.S.)
Natural Gas-fired: 87 (3% total U.S.)
Nuclear: 5 (4% total U.S.)
Hydro-electric: 157 (5% total U.S.)
Other Renewable: 24 (1% total U.S.)

- How does this relate to my new Tesla?
- Do you really think that when I connect my new Tesla, all 334 power plants will change their output?
- What if, instead, we remove an electric load, will all 334 power plants stop generating 1 Watt each to accommodate to the new demand?

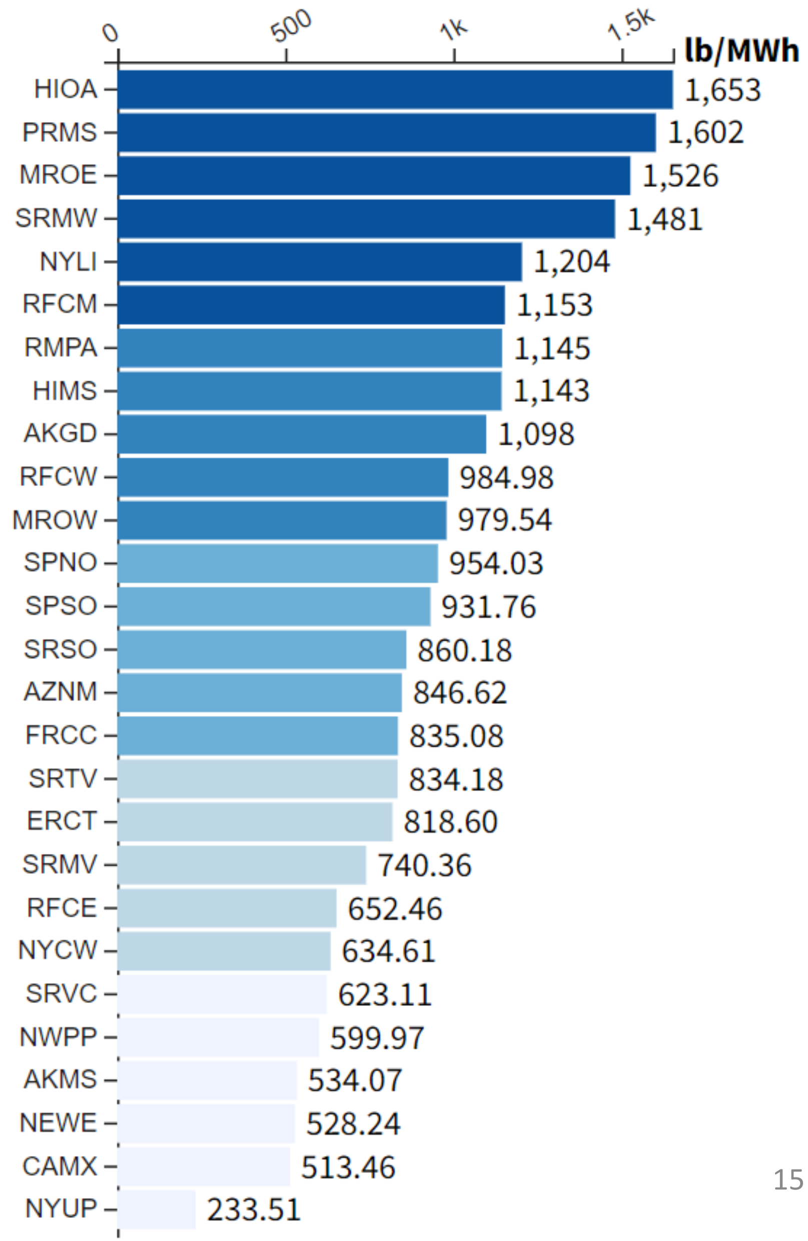
https://www.energy.gov/sites/prod/files/2016/09/f33/NY_Energy%20Sector%20Risk%20Profile_0.pdf

CO₂ total output emission rate (lb/MWh) by eGRID subregion, 2020



Sort A to Z | Sort by Amount

US: 818.29 (lb/MWh)



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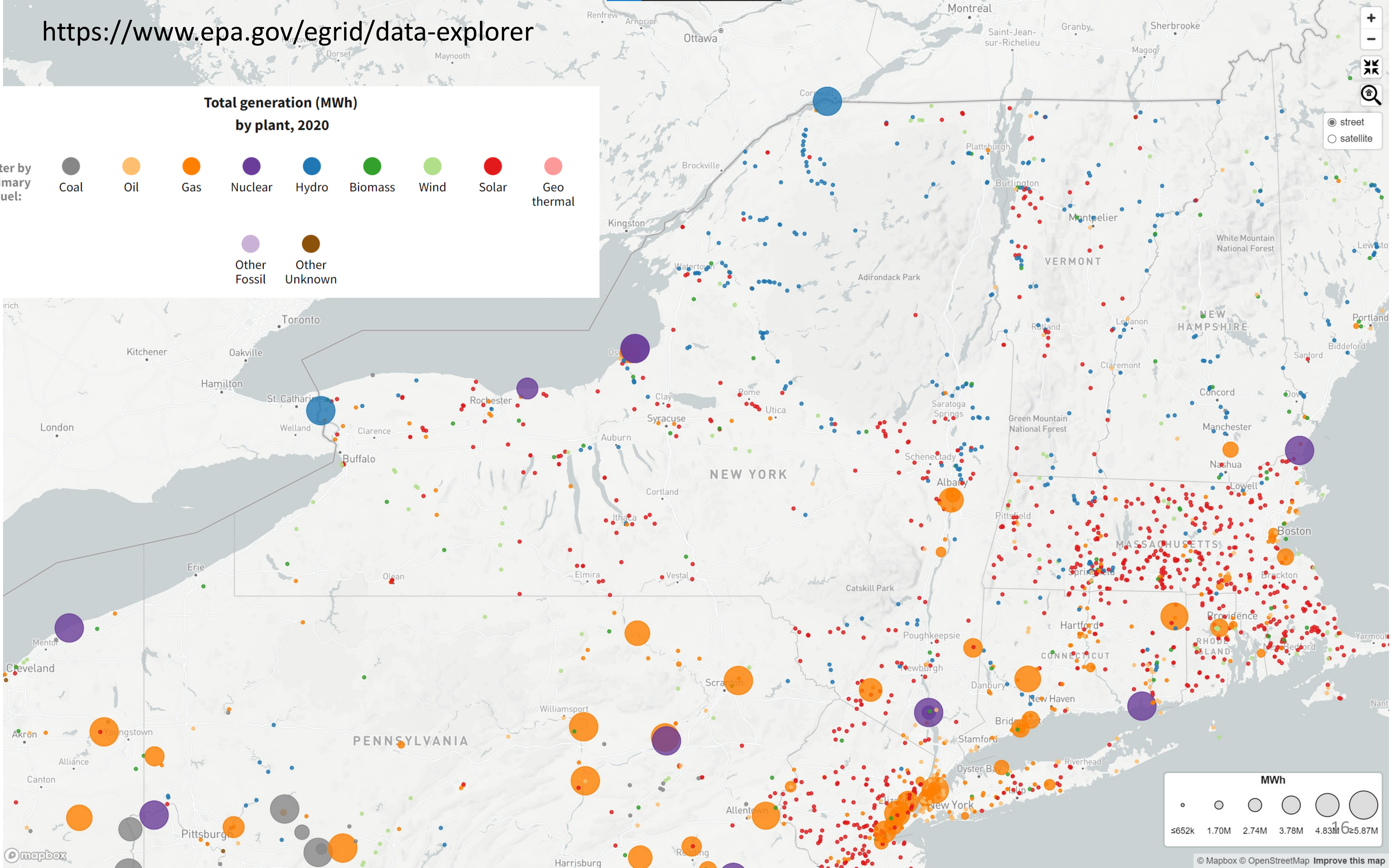
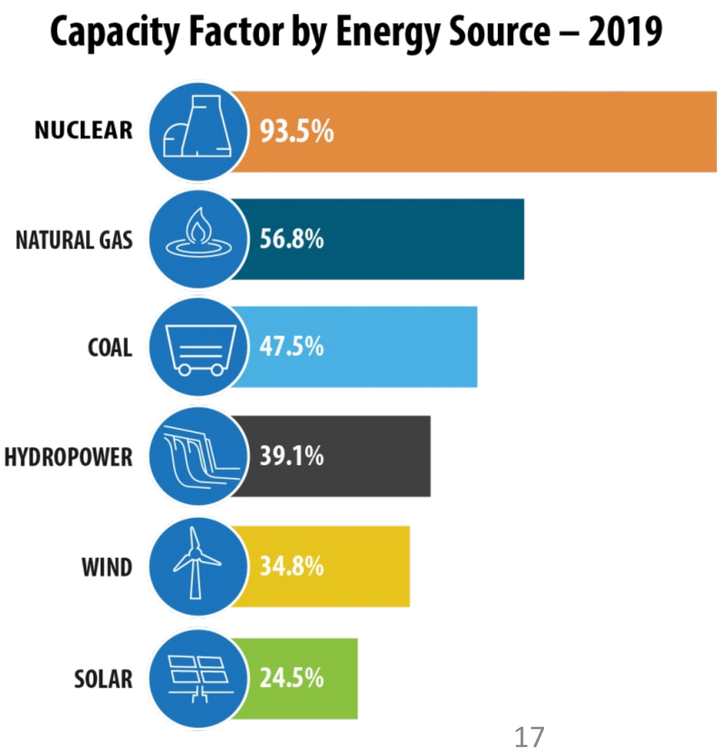


Do all +300 power plants respond to changes in demand?

- The answers is: probably not. If not all, which plants do?
- Let’s go back to eGRID: non-baseload output emission rate

- What is baseload? What isn’t baseload?
  - Some power plants operate close to 100% of the time, while other plants only operate few hours of the year
  - In the data, we can check in the Capacity Factor (CF)
    - High CF > Cheaper > Used more > Lower in the dispatch stack
    - Low CF > Costlier > Used less > Higher in the dispatch stack
  - What happens when demand changes?
    Which plants are more ‘vulnerable’, ‘affected’,
    or more likely to respond?

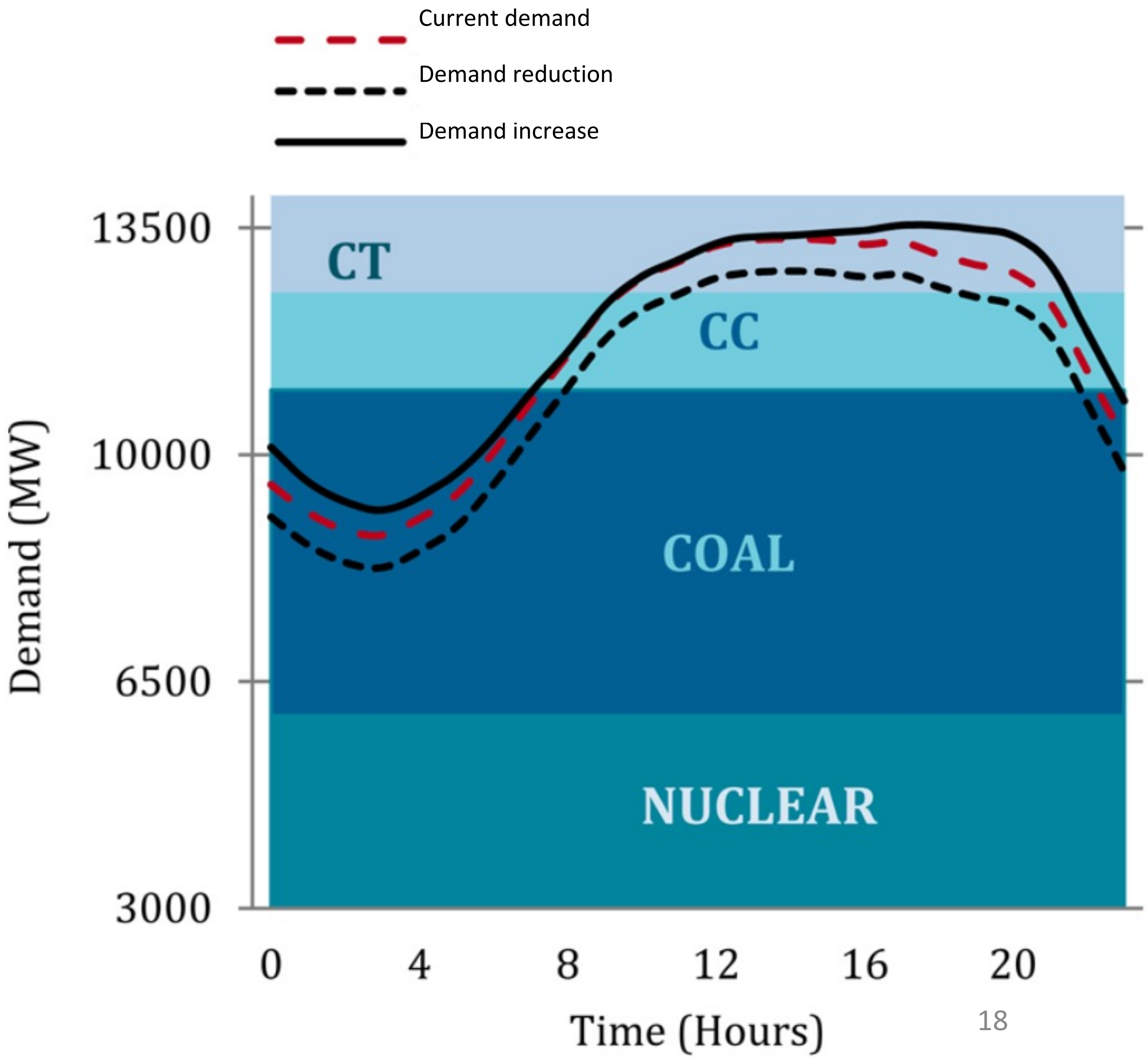


What happens when demand changes? Which plants are more ‘vulnerable’, ‘affected’, or more likely to respond?

The answers is: those power plants with low capacity factors, also known as:

- At the margin (of the dispatch stack)
- Non-baseload
- Peaker plants

https://pubs.acs.org/doi/abs/10.1021/acs.est.5b05216

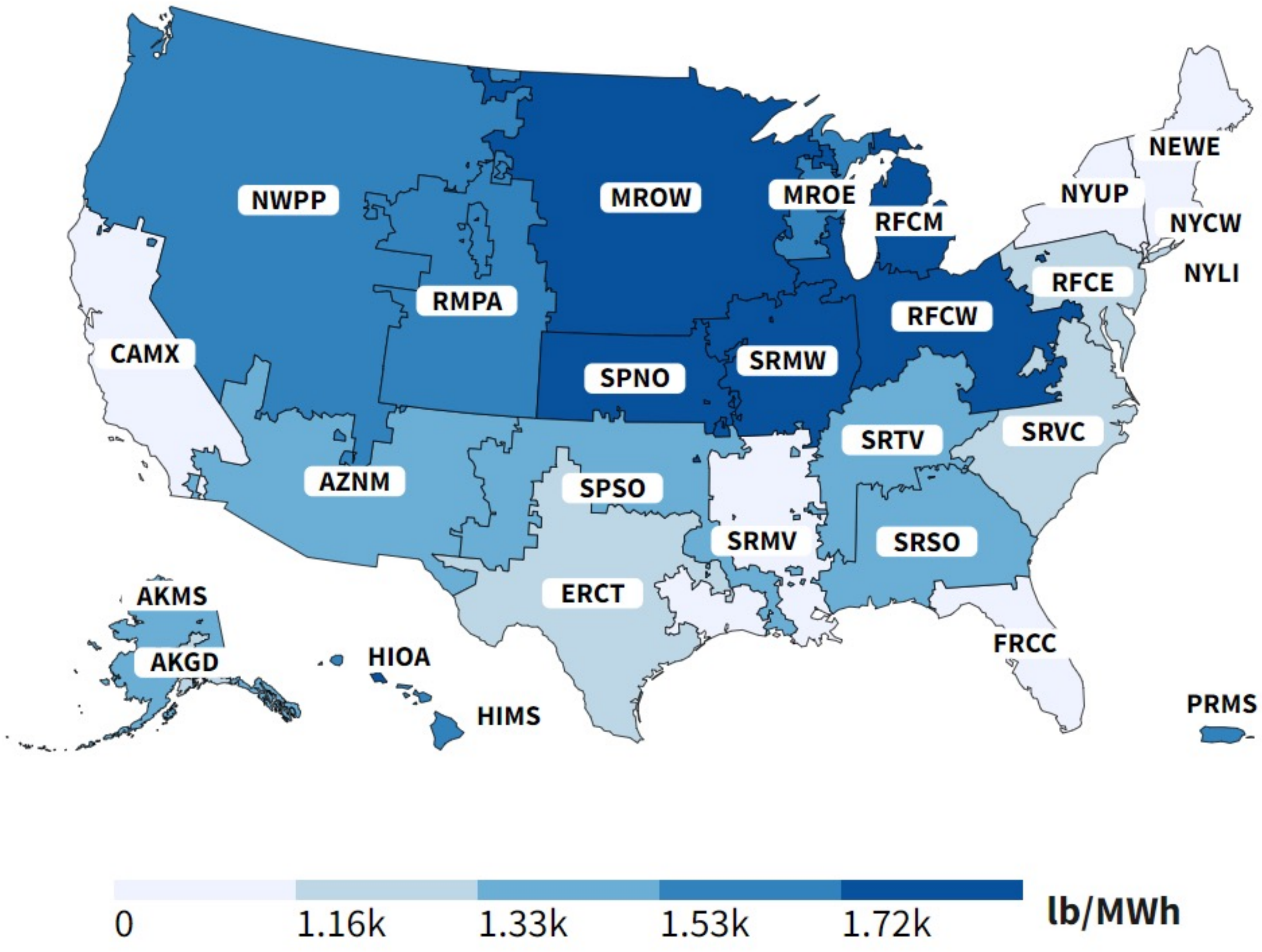


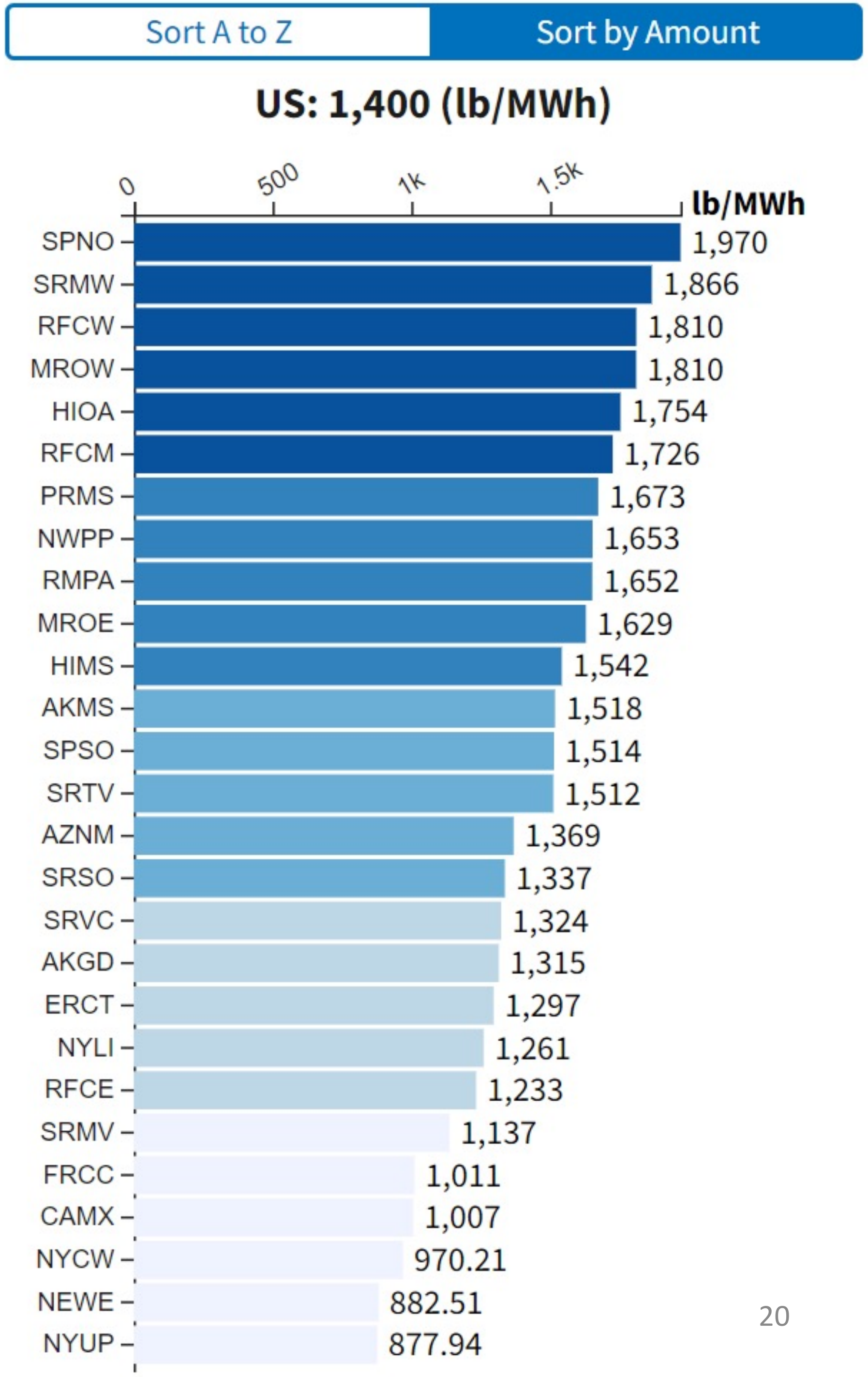
Do all +300 power plants respond to changes in demand?

- The answers is: probably not. If not all, which plants do?
- Let’s go back to eGRID: non-baseload output emission rate
  - This means: from the complete database with total emissions and generation, filter only those fuel-burning power plants with a capacity factor less than 80%, and then divide emissions by generation

- New York Upstate is 878 lb/MWh
- Again, the lowest of the country? Yes.
- Still, non-baseload output emission rate is 4 times greater than total output emission rate

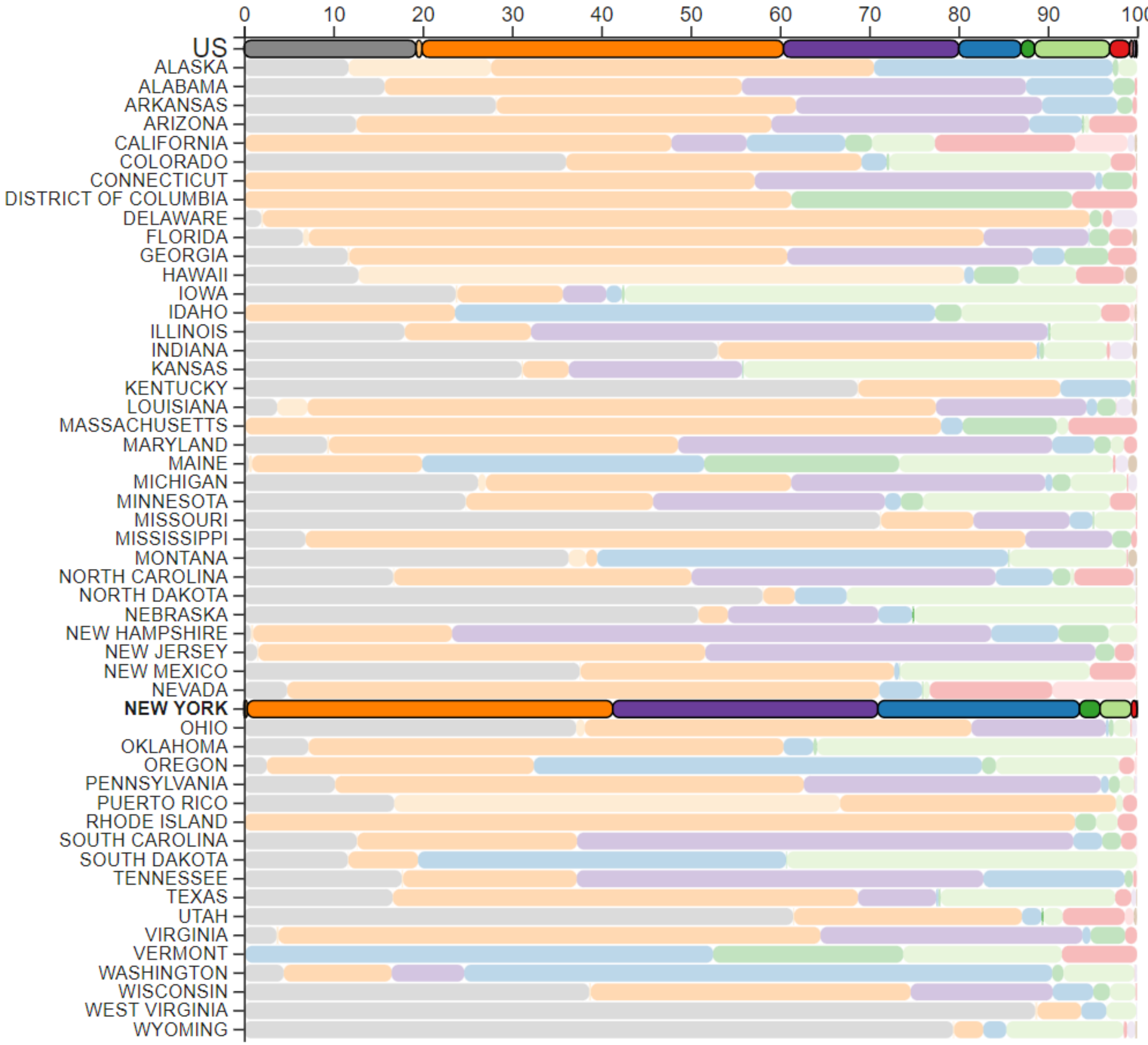
CO_2 non-baseload output emission rate (lb/MWh) by eGRID subregion, 2020





https://www.epa.gov/egrid/data-explorer

Resource Mix by all fuel types by state, 2020



Generation by Fuel Type	US Resource Mix (%)	NEW YORK Resource Mix (%)
Coal	19.28	0.11
Oil	0.66	0.27
Gas	40.47	40.92
Nuclear	19.64	29.69
Hydro	6.96	22.57
Biomass	1.54	2.29
Wind	8.40	3.49
Solar	2.22	0.65
Geo thermal	0.40	0.00
Other Fossil	0.31	0.00
Other Unknown	0.12	0.00

Why is this distinction important, between total vs non-baseload?

- Emissions over 1 year of driving my Tesla 10 miles every weekday to come to RIT instead of using my bicycle for that purpose:
  - Electricity use = 540 kWh/year
    (45 weeks/year * 5 weekdays/week * 10 miles/weekday * 0.24 kWh/mile)
  - With total output emission rate:
    540 kWh/year * 234 lb/MWh * (1 MWh/1,000 kWh) = 126 lb/year
  - With non-baseload output emission rate:
    540 kWh/year * 880 lb/MWh * (1 MWh/1,000 kWh) = 475 lb/year
- Which is closer to reality?

Which is closer to reality?

Approach	Emissions estimate	Comment
Total output emission rate	126 lb/year	Assume all plants respond to demand change, an average effect
Non-baseload output emission rate	475 lb/year	Assume only plants at the margin or non-baseload respond to the change, a marginal effect

The marginal effect is considered to be more appropriate when estimating the emissions effect of changes to the electricity grid.

This is not widely known, and many people end up assuming an average effect when the application is marginal.

Approach in eGRID	Total output emission rate	Non-baseload emission rate
Analysis type	Attributional – assign environmental *responsibility*	Consequential – asses environmental *impact*
Examples of questions answered	How do emissions distribute among all loads? What are the emissions embedded in cement?	How do emissions change as a response to a change in demand?
Other synonyms or equivalent applications	Average emission factor, carbon intensity	Marginal emission factor
Application	Carbon footprint calculators Life Cycle Analysis	Decision-making about the grid: When to use/store energy? Where to site a new energy asset? How dirty can new technologies be?

What we know:

$\boldsymbol{D_t}$

Vector with hourly data on electricity demand

$\boldsymbol{E(D_t)}$

Vector with hourly data on grid emissions

$\boldsymbol{\Delta D_t}$

Vector with hourly data on change in electricity demand

What we want:

$\boldsymbol{E(\Delta D_t)}$

Emissions of new technology

How they do it:

Simulation approach

$$\boldsymbol{E(\Delta D_t) = E(D'_t) - E(D_t)}$$

Emissions of new technology

Empirical approaches

$$\boldsymbol{E(\Delta D_t)} = ?$$

Emissions of new technology

We know emissions are a function of demand change.
But how does this function look like?
This is where people diverge.

$\boldsymbol{E(\Delta D_t)} =$?

Emissions of new technology

Approximation methods

(Eq 1) $$Average\ effect = \frac{Y_t}{X_t} = \frac{Emissions\ _t[lbs]}{Generation\ _t[MWh]}$$

(Eq 2) $$E(\Delta D_t) = AEF\ \left[\frac{lbs}{MWh}\right] = \frac{1}{T}\sum_{t=1}^{T} \frac{Emissions\ _t[lbs]}{Generation\ _t[MWh]}$$

Marginal change in demand → marginal change in emissions

Marginal change in demand		Existing demand		New demand
ΔD_t	+	D_t	=	D'_t
Marginal change in emissions		**Existing emissions**		**New emissions**
$\Delta E(D_t)$	+	$E(D_t)$	=	$E(D')_t$

$\boldsymbol{E}(\Delta \boldsymbol{D_t}) = ?$

Emissions of new technology

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(Eq 1) $$Average\ effect = \frac{Y_t}{X_t} = \frac{Emissions\ _t[lbs]}{Generation\ _t[MWh]}$$

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(Eq 3) $$Marginal\ effect = \frac{Y_t - Y_{t-1}}{X_t - X_{t-1}} = \frac{\Delta Y}{\Delta X}$$

(Eq 4) $$Marginal\ effect = \frac{Emissions_t - Emissions_{t-1}}{Generation_t - Generation_{t-1}} = \frac{\Delta Emissions\ [lbs]}{\Delta Generation\ [Mwh]}$$

$\boldsymbol{E}(\Delta \boldsymbol{D_t}) =$?

Emissions of new technology

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(Eq 5) $$E(\Delta D_t) = MEF[\frac{lbs}{MWh}] = \frac{1}{T}\sum_{t=1}^{T} \frac{Emissions_t - Emissions_{t-1}}{Generation_t - Generation_{t-1}}$$

(Eq 6) $$\Delta Y = \beta * \Delta X$$

$\boldsymbol{E(\Delta D_t)} = ?$

Emissions of new technology

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(Eq 7) $\Delta\ emissions = MEF * \Delta\ \boldsymbol{total}\ generation$

$\boldsymbol{E}(\Delta \boldsymbol{D_t})$ = ?

Emissions of new technology

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(Eq 8) $$\Delta\ emissions = MEF * \Delta\ \boldsymbol{thermal}\ \ generation$$

$\boldsymbol{E}(\Delta \boldsymbol{D_t}) = ?$

Emissions of new technology

Approximation methods

Average Emissions Factor (AEF) →

(Eq 1) $Average\ effect = \frac{Y_t}{X_t} = \frac{Emissions\ _t[lbs]}{Generation\ _t[MWh]}$

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Emissions of new technology

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Demand Marginal Emissions Factor (Demand MEF)

(Eq 6) $\Delta Y = \beta * \Delta X$

(Eq 7) $\Delta\ emissions = MEF * \Delta\ \boldsymbol{total}\ generation$

(Eq 8) $\Delta\ emissions = MEF * \Delta\ \boldsymbol{thermal}\ \ generation$

$\boldsymbol{E(\Delta D_t)} = ?$

Emissions of new technology

Approximation methods

(Eq 1) $Average\ effect = \frac{Y_t}{X_t} = \frac{Emissions\ _t[lbs]}{Generation\ _t[MWh]}$

Average Emissions Factor (AEF)

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(Eq 6) $\Delta Y = \beta * \Delta X$

Demand Marginal Emissions Factor (Demand MEF)

(Eq 7) $\Delta\ emissions = MEF * \Delta\ \boldsymbol{total}\ generation$

Thermal Marginal Emissions Factor (Demand MEF)

(Eq 8) $\Delta\ emissions = MEF * \Delta\ \boldsymbol{thermal}\ \ generation$

$\boldsymbol{E}(\Delta \boldsymbol{D_t})$ = ?

Emissions of new technology

Approximation methods

Average Emissions Factor (AEF) (Eq 2) $E(\Delta D_t) = AEF \left[\frac{lbs}{MWh}\right] = \frac{1}{T}\sum_{t=1}^{T} \frac{Emissions_{\ t}[lbs]}{Generation_{\ t}[MWh]}$

Demand MEF (Eq 7) $\Delta\, emissions = MEF * \Delta\, \boldsymbol{total}\ generation$

Thermal MEF (Eq 8) $\Delta\, emissions = MEF * \Delta\, \boldsymbol{thermal}\ generation$

Costliest MEF Take the emissions rate of the costliest plant dispatched

Incremental MEF Simulate the addition of 1 kWh

$$E(\Delta D_t) = ?$$

Emissions of new technology

Approximation methods

Average Emissions Factor (AEF) (Eq 2) $E(\Delta D_t) = AEF\left[\frac{lbs}{MWh}\right] = \frac{1}{T}\sum_{t=1}^{T}\frac{Emissions_{\ t}[lbs]}{Generation_{\ t}[MWh]}$

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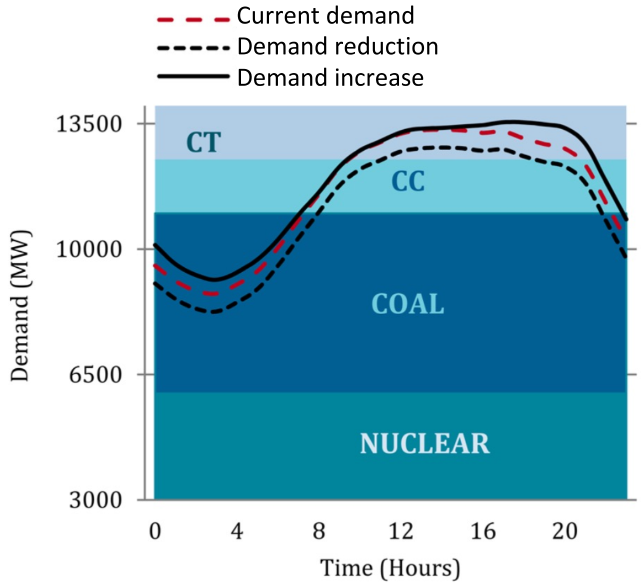
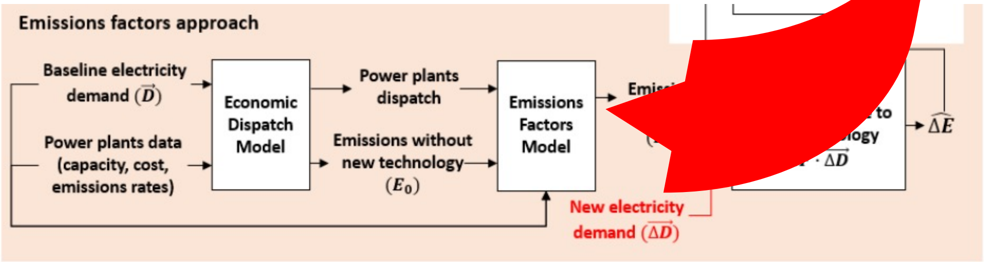


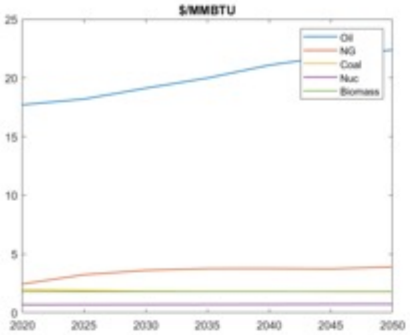
Approximation methods

Average Emissions Factor (AEF)	(Eq 2)	$E(\Delta D_t) = AEF\left[\frac{lbs}{MWh}\right] = \frac{1}{T}\sum_{t=1}^{T}\frac{Emissions_{\ t}[lbs]}{Generation_{\ t}[MWh]}$
Demand MEF	(Eq 7)	$\Delta\, emissions = MEF * \Delta\, \boldsymbol{total}\ generation$
Thermal MEF	(Eq 8)	$\Delta\, emissions = MEF * \Delta\, \boldsymbol{thermal}\ \ generation$
Costliest MEF		Take the emissions rate of the costliest plant dispatched
Incremental MEF		Simulate the addition of 1 kWh



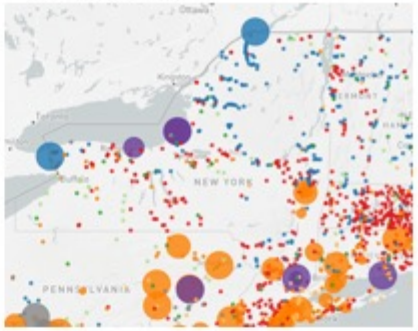
- We have reviewed all approximation methods
- We have learned the difference between average vs marginal
- What about the simulator? How does that work?

Fuel prices ($/MMBTU)

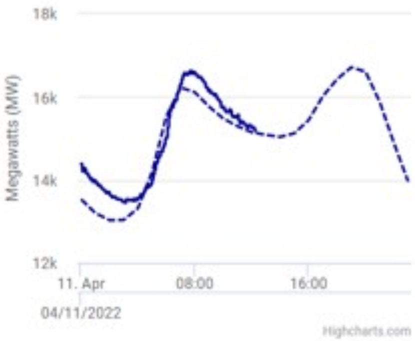


Power plant data:

- Nameplate capacity (MW)
- Ramping rates (% of capacity per hour or MWh/h)
- Heat rate (MMBTU/MWh)
- O&M costs

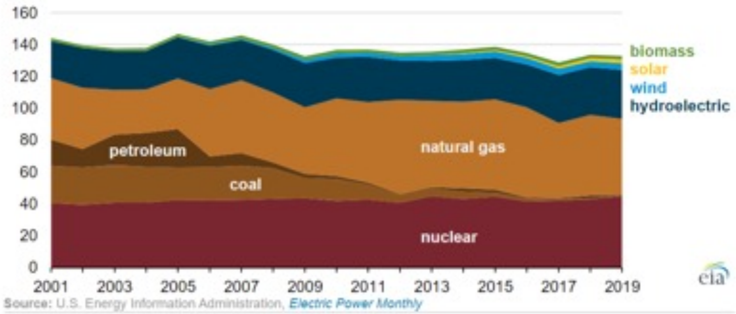


Demand (MW)

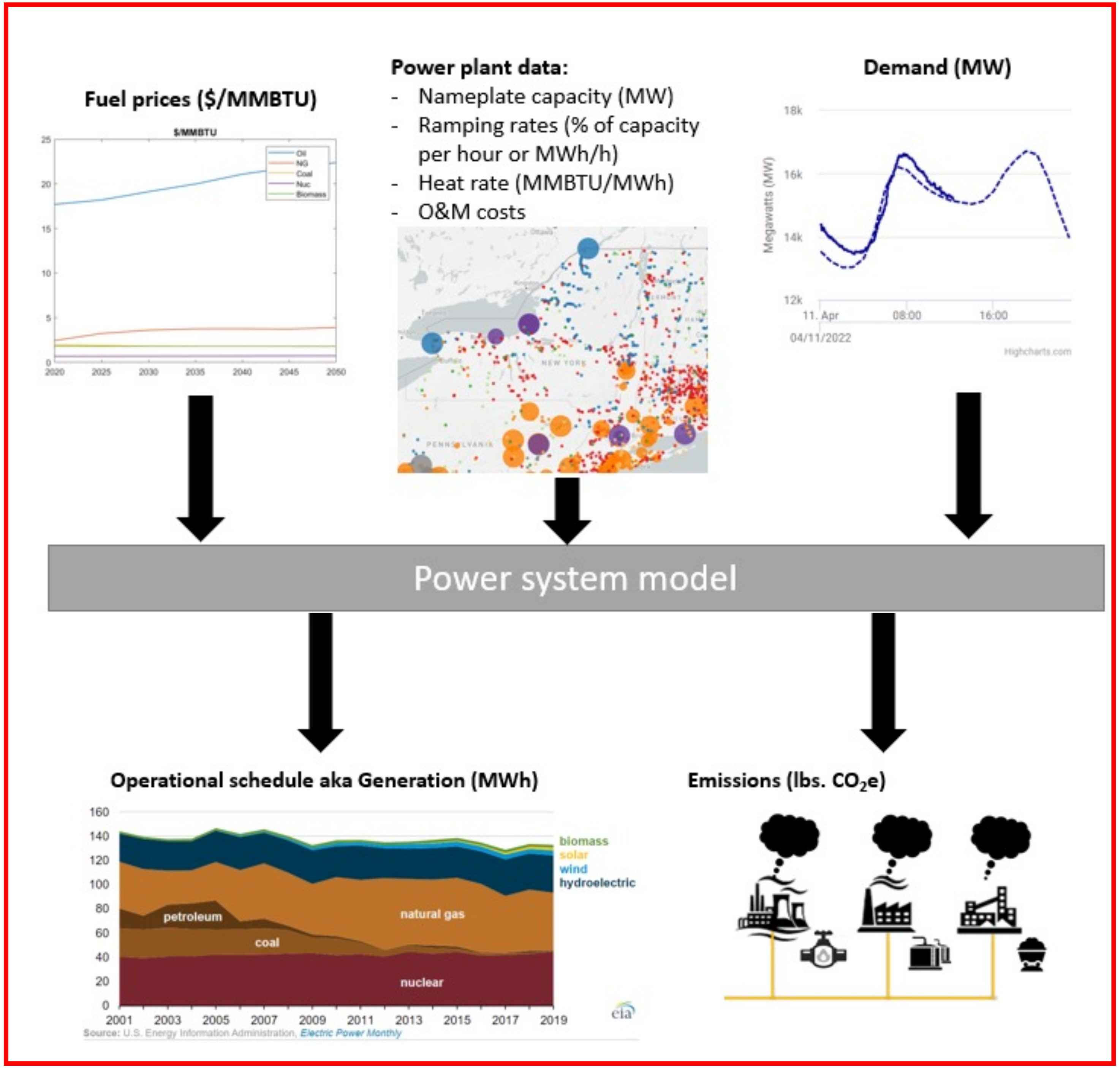


Power system model

Operational schedule aka Generation (MWh)



Emissions (lbs. CO_2e)


Fuel prices ($/MMBTU)
Power plant data:
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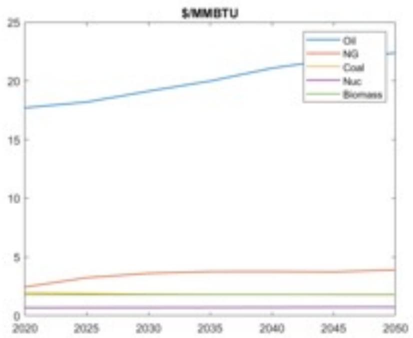
- O&M costs
Demand (MW)
Megawatts (MW)
04/11/2022
Highcharts.com
Power system model
Operational schedule aka Generation (MWh)
biomass
solar
wind
hydroelectric
natural gas
petroleum
coal
nuclear
Source: U.S. Energy Information Administration, Electric Power Monthly
Emissions (lbs. CO_2e)

Fuel prices ($/MMBTU)



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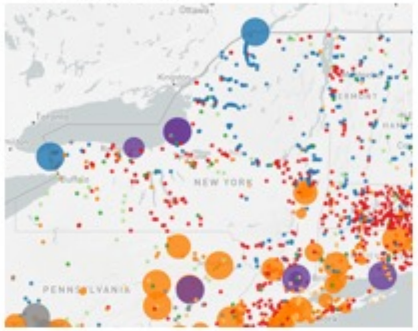
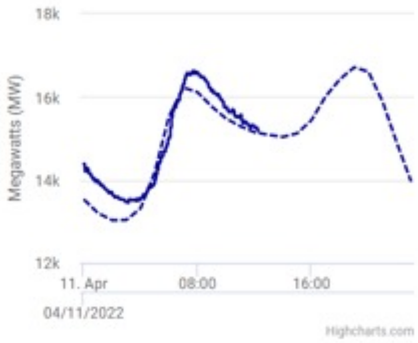
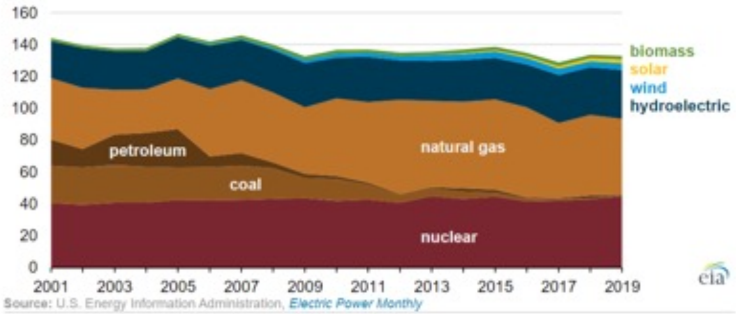


Demand (MW)

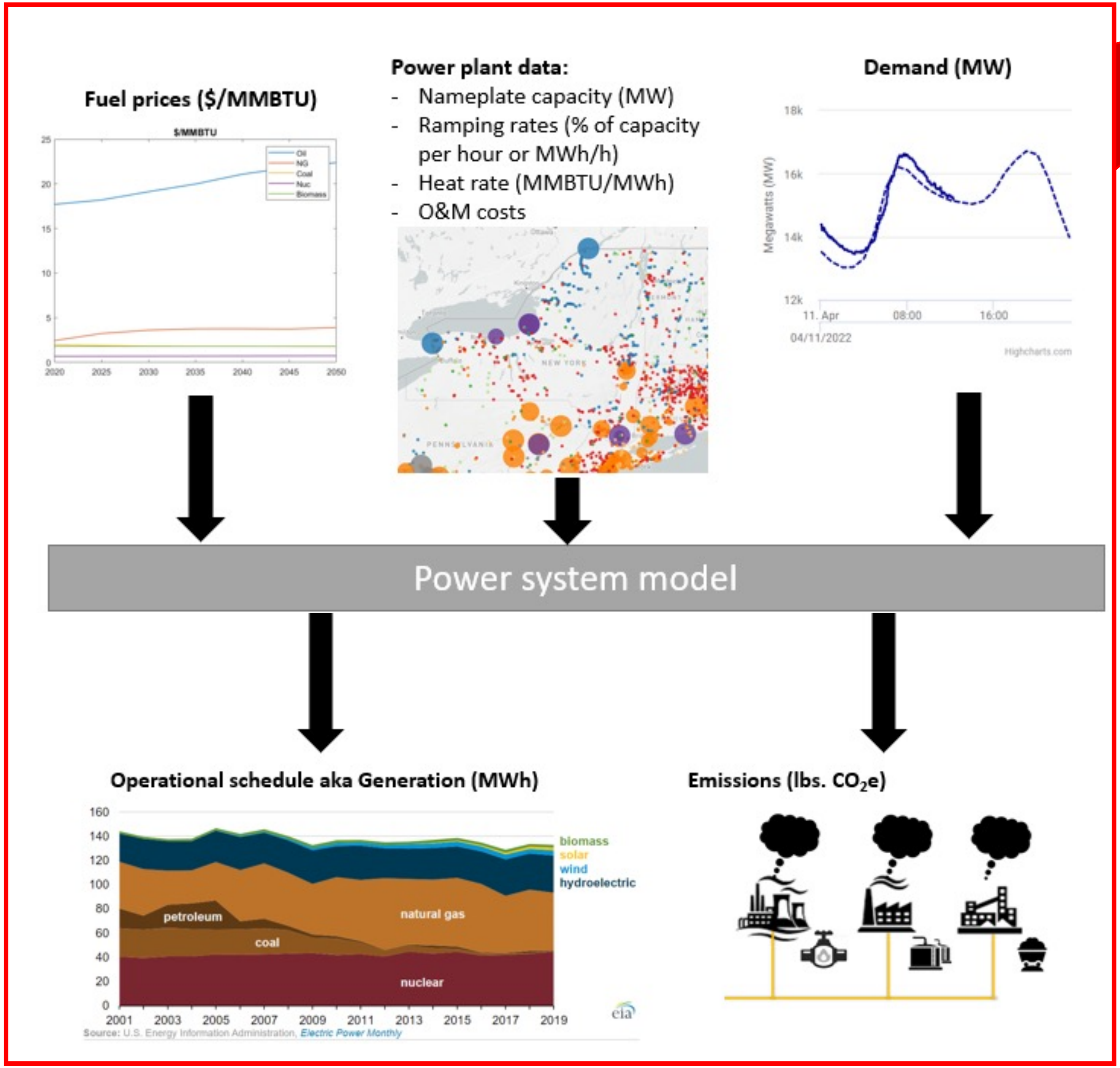


Power system model

Operational schedule aka Generation (MWh)



Emissions (lbs. CO_2e)



Fuel prices ($/MMBTU)
$/MMBTU
Oil
NG
Coal
Nuc
Biomass
Power plant data:
- Nameplate capacity (MW)
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Demand (MW)
Megawatts (MW)
18k
16k
14k
12k
11. Apr
08:00
16:00
04/11/2022
Highcharts.com
Power system model
Operational schedule aka Generation (MWh)
biomass
solar
wind
hydroelectric
petroleum
natural gas
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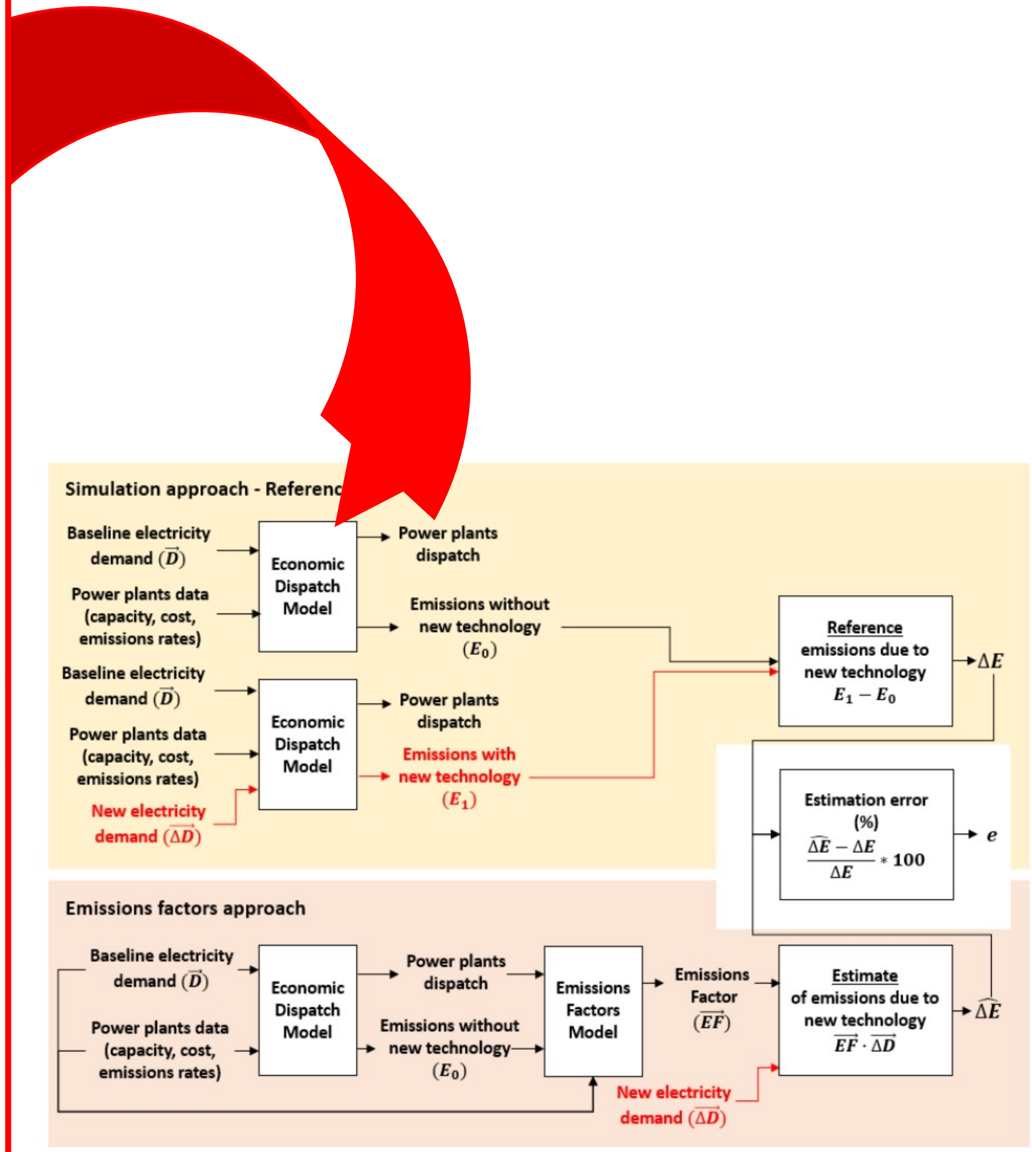
Emissions (lbs. CO_2e)



Simulation approach - Referenc
Baseline electricity demand $(\vec{D})$
Power plants data (capacity, cost, emissions rates)
Economic Dispatch Model
Power plants dispatch
Emissions without new technology (E_0)
Baseline electricity demand $(\vec{D})$
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ΔE
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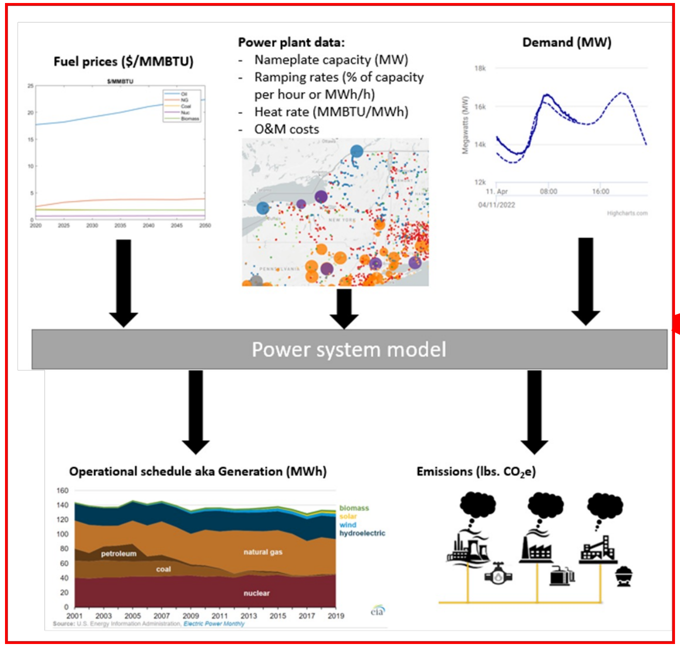
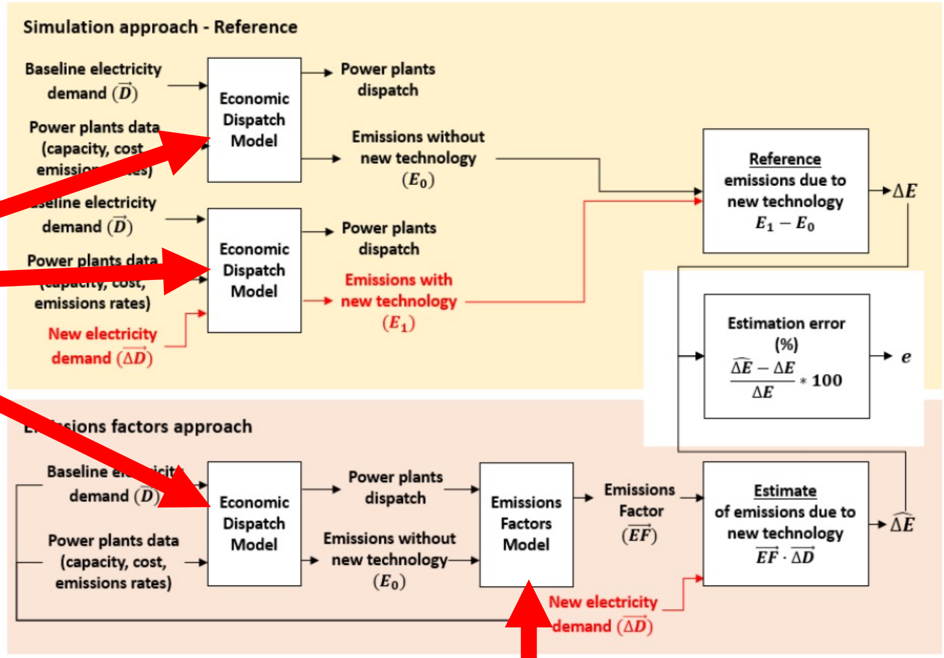




Approximation methods

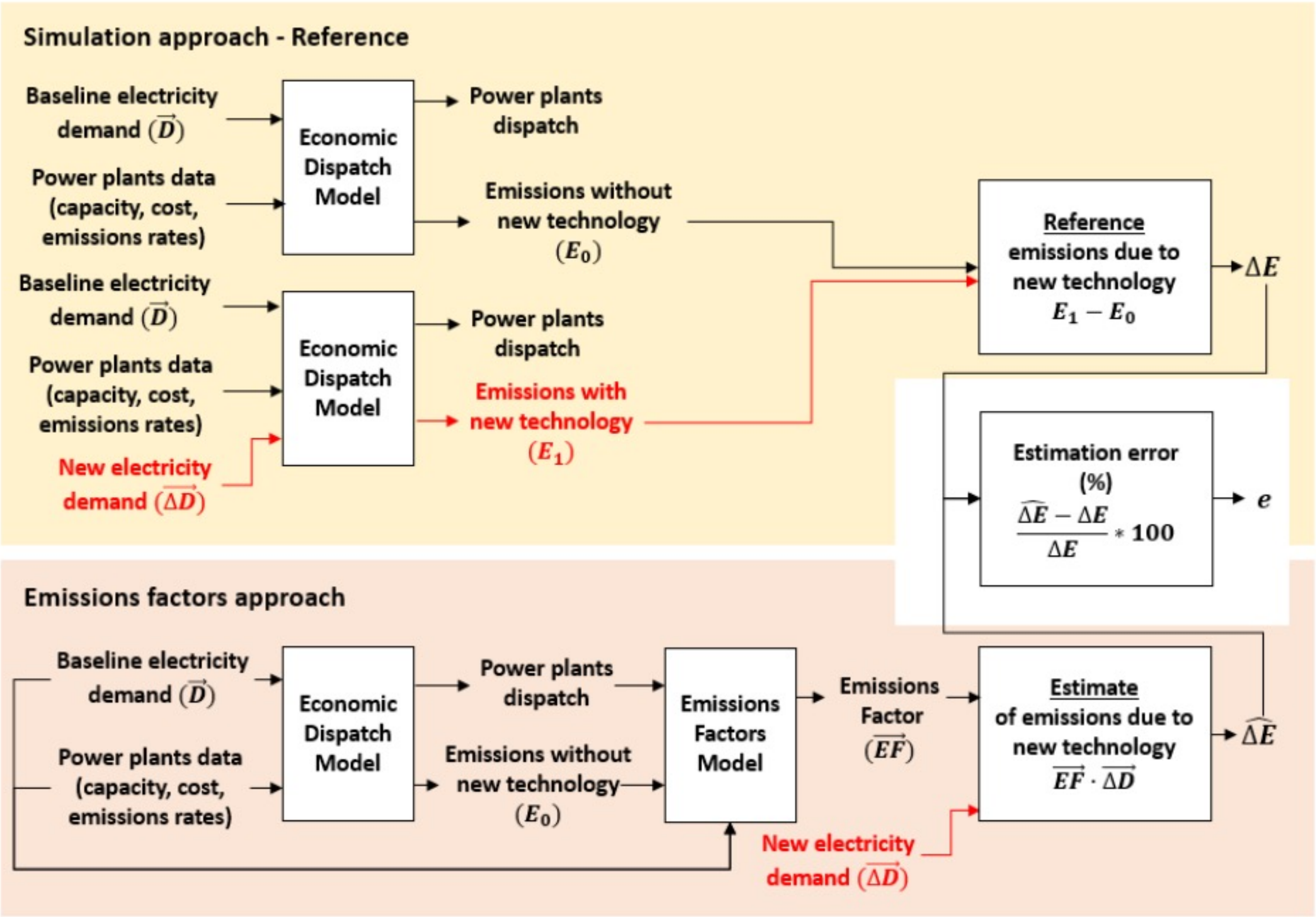
Average Emissions Factor (AEF) (Eq 2) $E(\Delta D_t) = AEF\left[\frac{lbs}{MWh}\right] = \frac{1}{T}\sum_{t=1}^{T}\frac{Emissions_{\,t}[lbs]}{Generation_{\,t}[MWh]}$

Demand MEF (Eq 7) $\Delta\, emissions = MEF * \Delta\, \boldsymbol{total}\ generation$

Thermal MEF (Eq 8) $\Delta\, emissions = MEF * \Delta\, \boldsymbol{thermal}\ generation$

Costliest MEF Take the emissions rate of the costliest plant dispatched

Incremental MEF Simulate the addition of 1 kWh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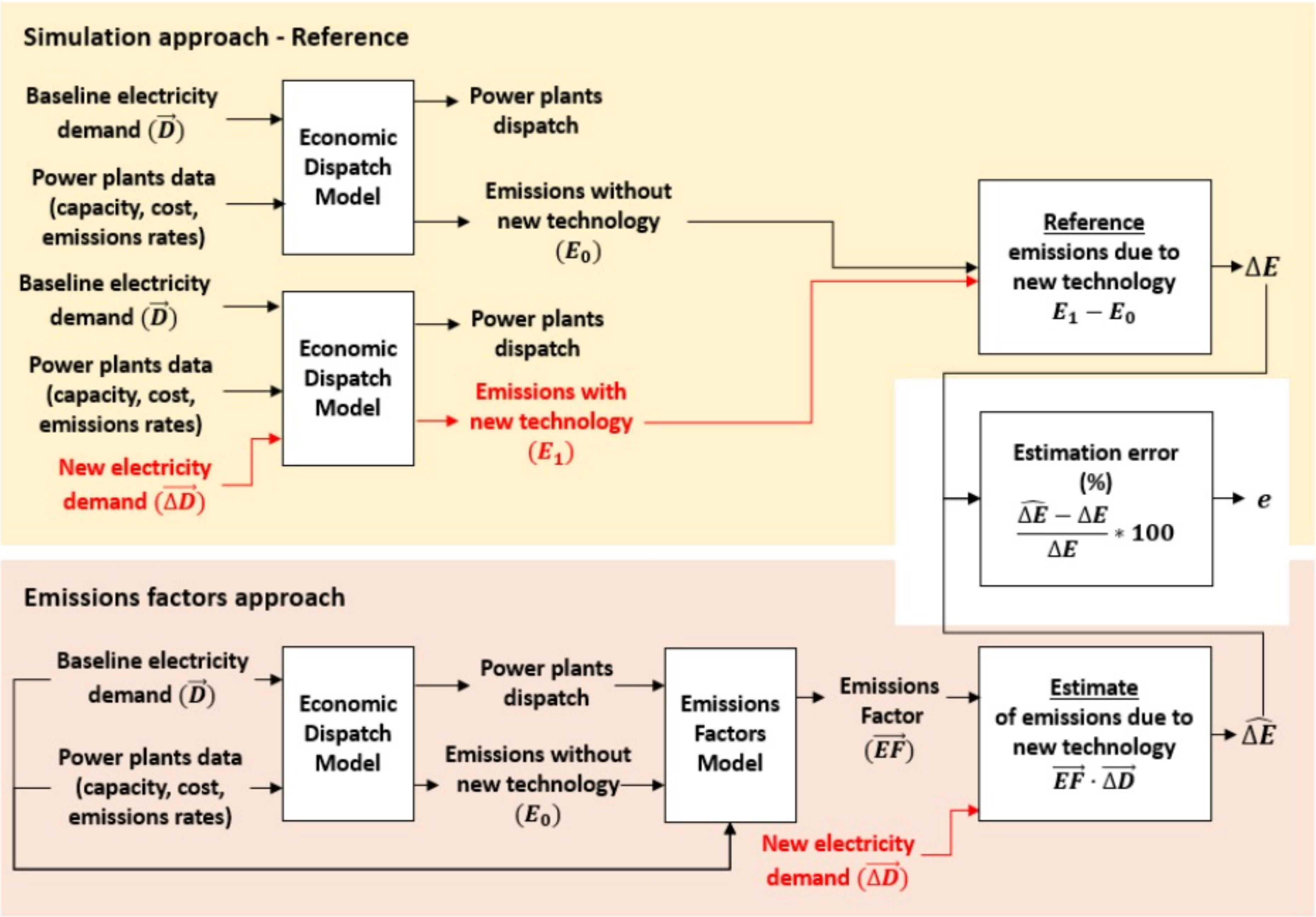
Method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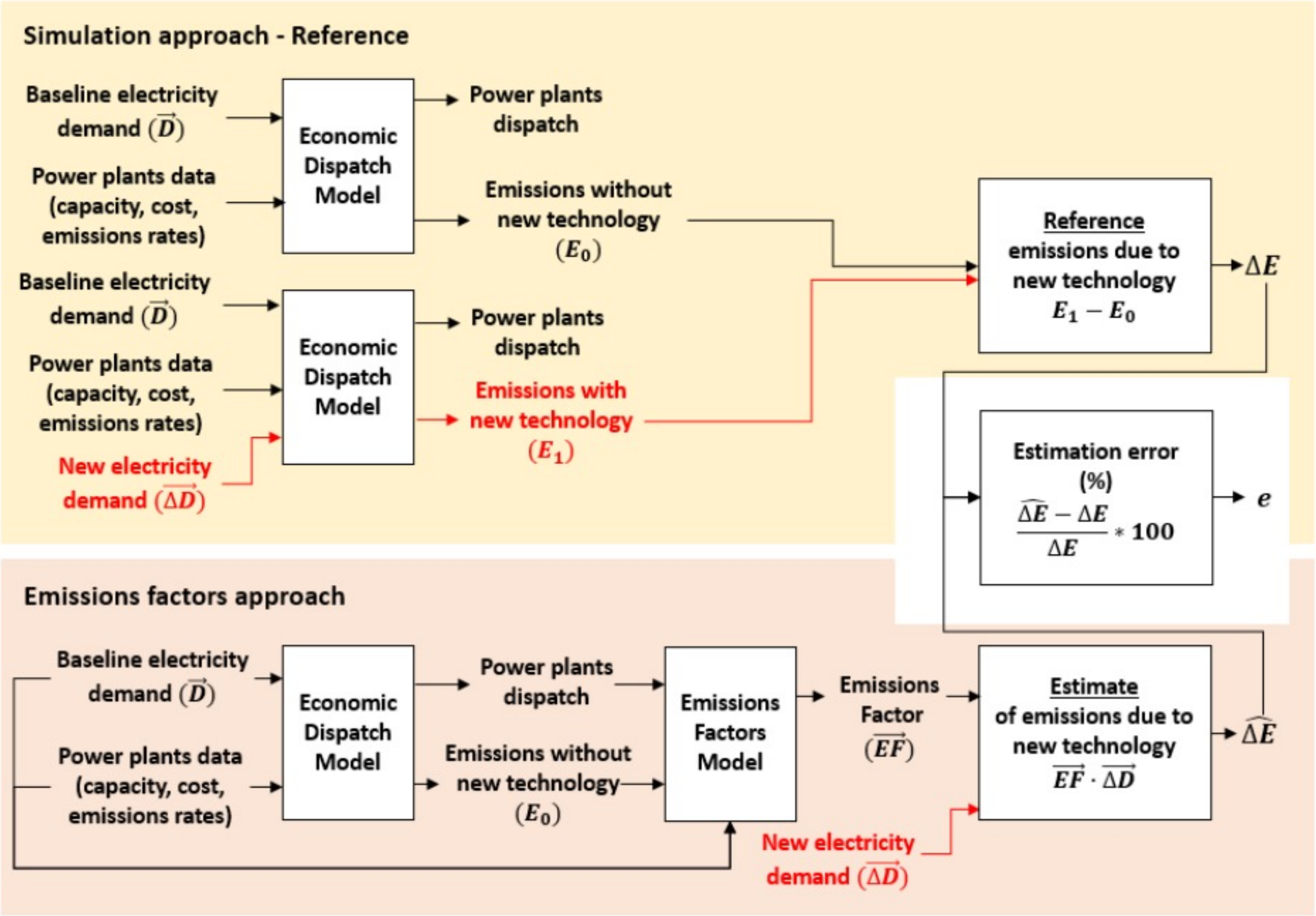
New electricity demand $(\overrightarrow{\Delta D})$

Method



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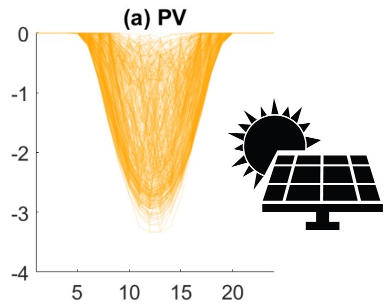
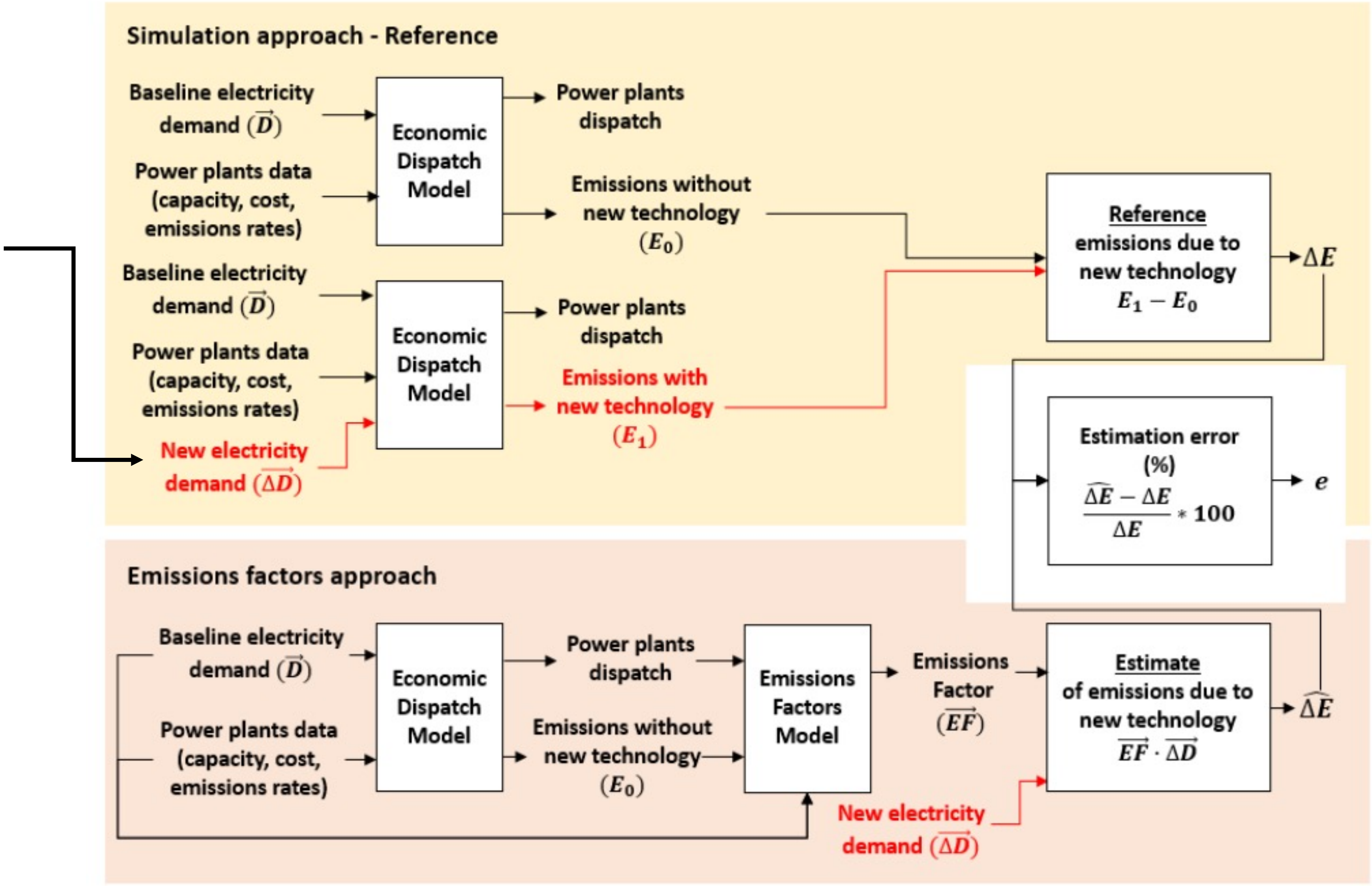

(a) PV
0
-1
-2
-3
-4
5
10
15
20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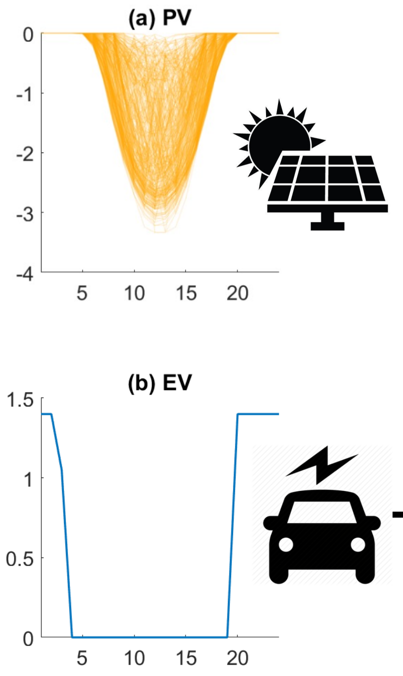
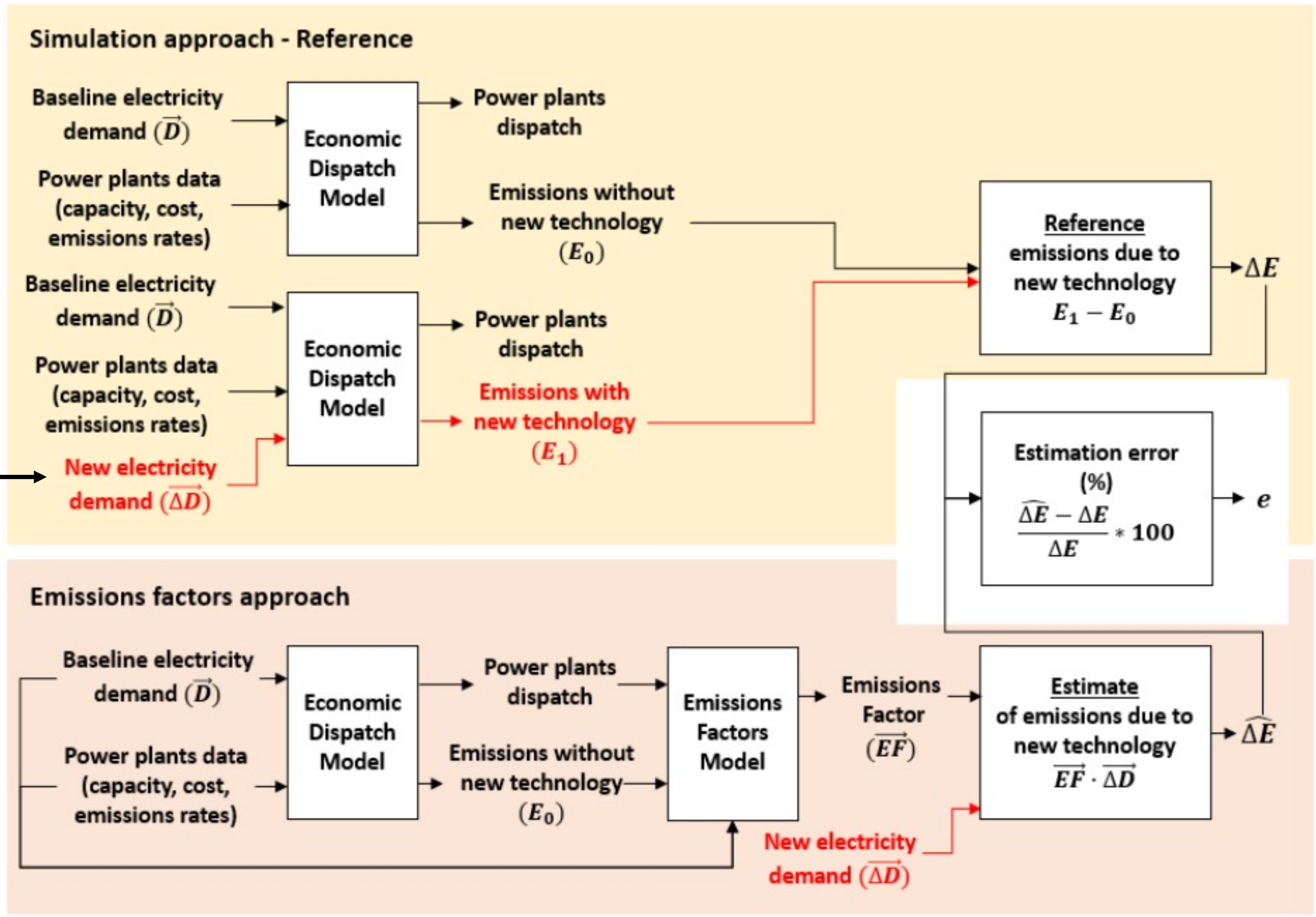


(a) PV
0
-1
-2
-3
-4
5
10
15
20
(b) EV
1.5
1
0.5
0
5
10
15
20



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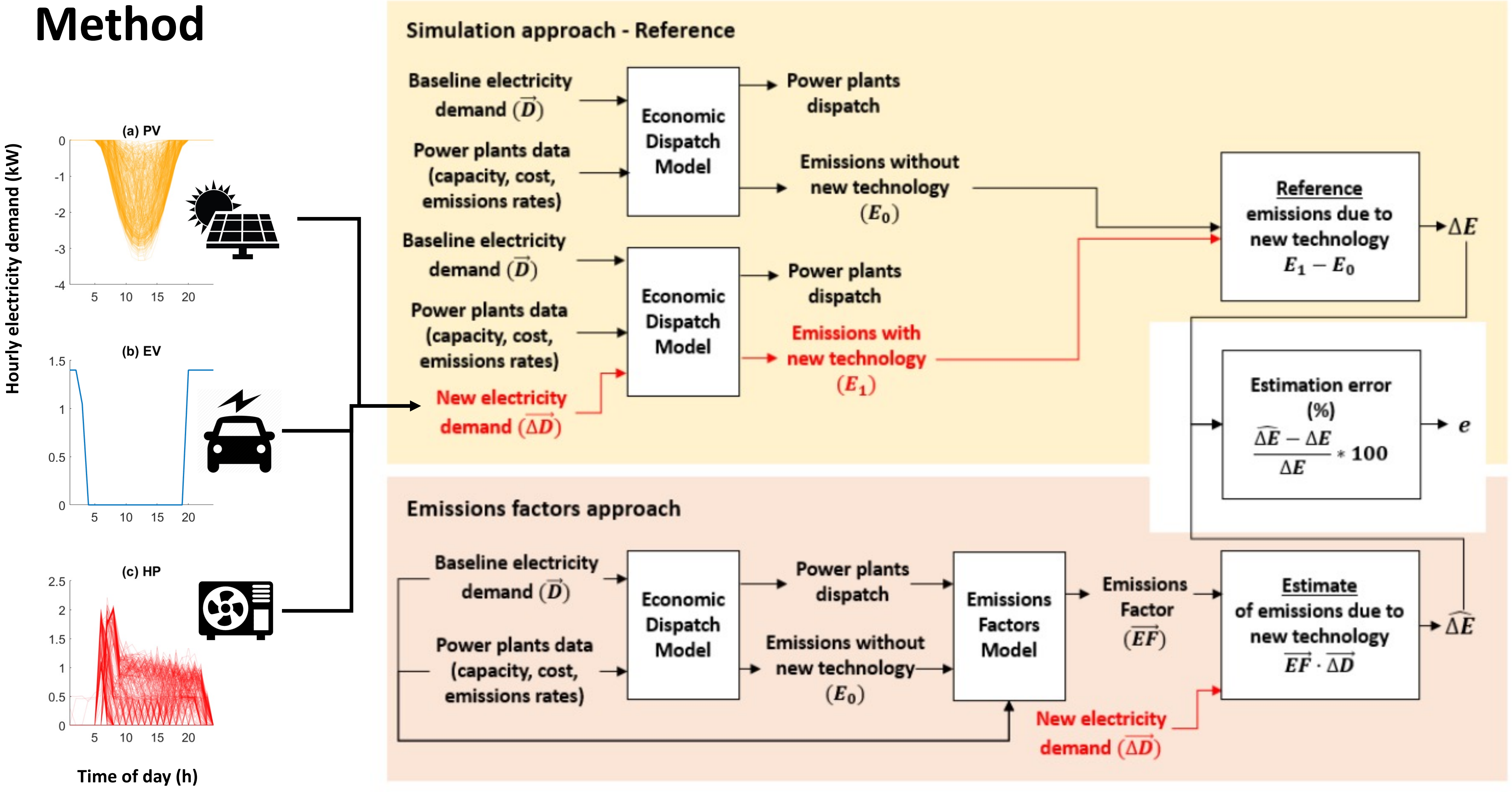

Hourly electricity demand (kW)
(a) PV
(b) EV
(c) HP
Time of day (h)
Simulation approach - Reference
Baseline electricity demand ($\vec{D}$)
Power plants data (capacity, cost, emissions rates)
Economic Dispatch Model
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Emissions with new technology (E_1)
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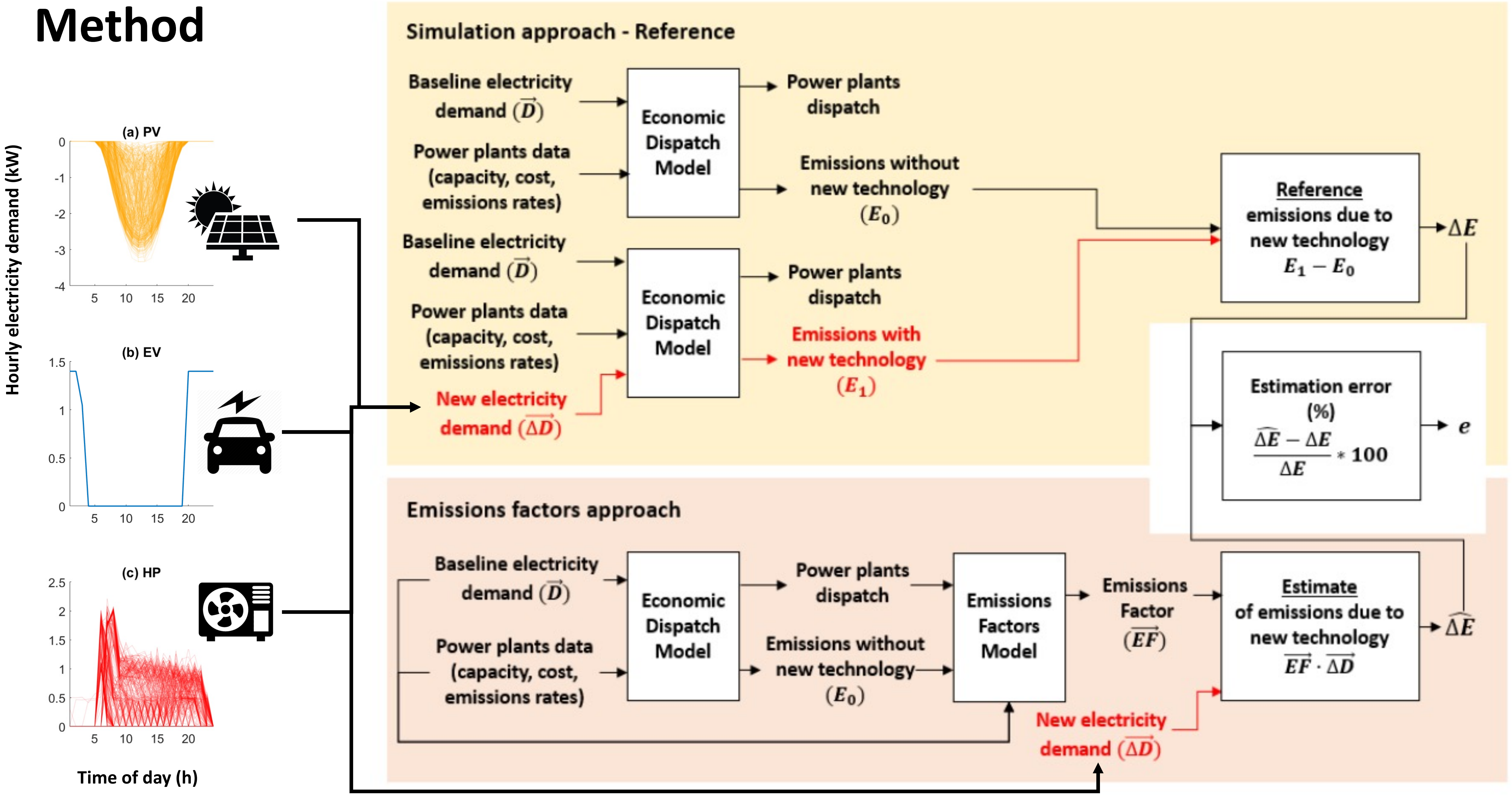

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(a) PV
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Time of day (h)
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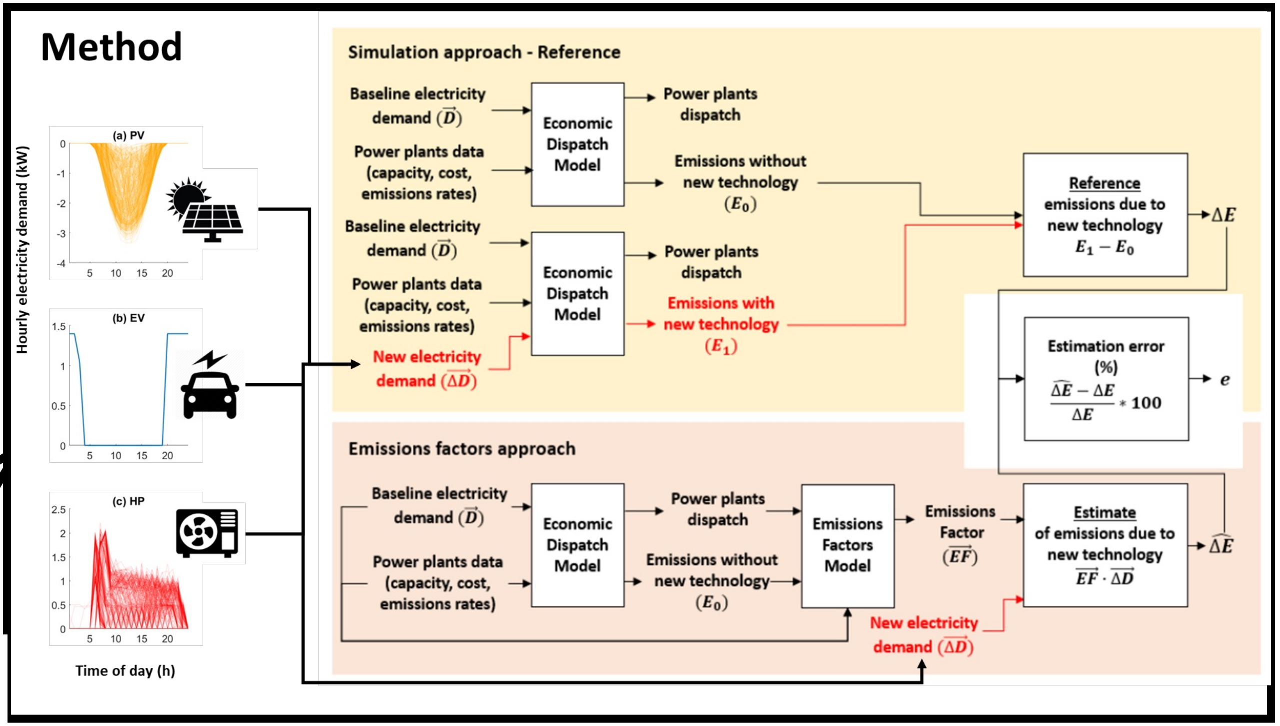
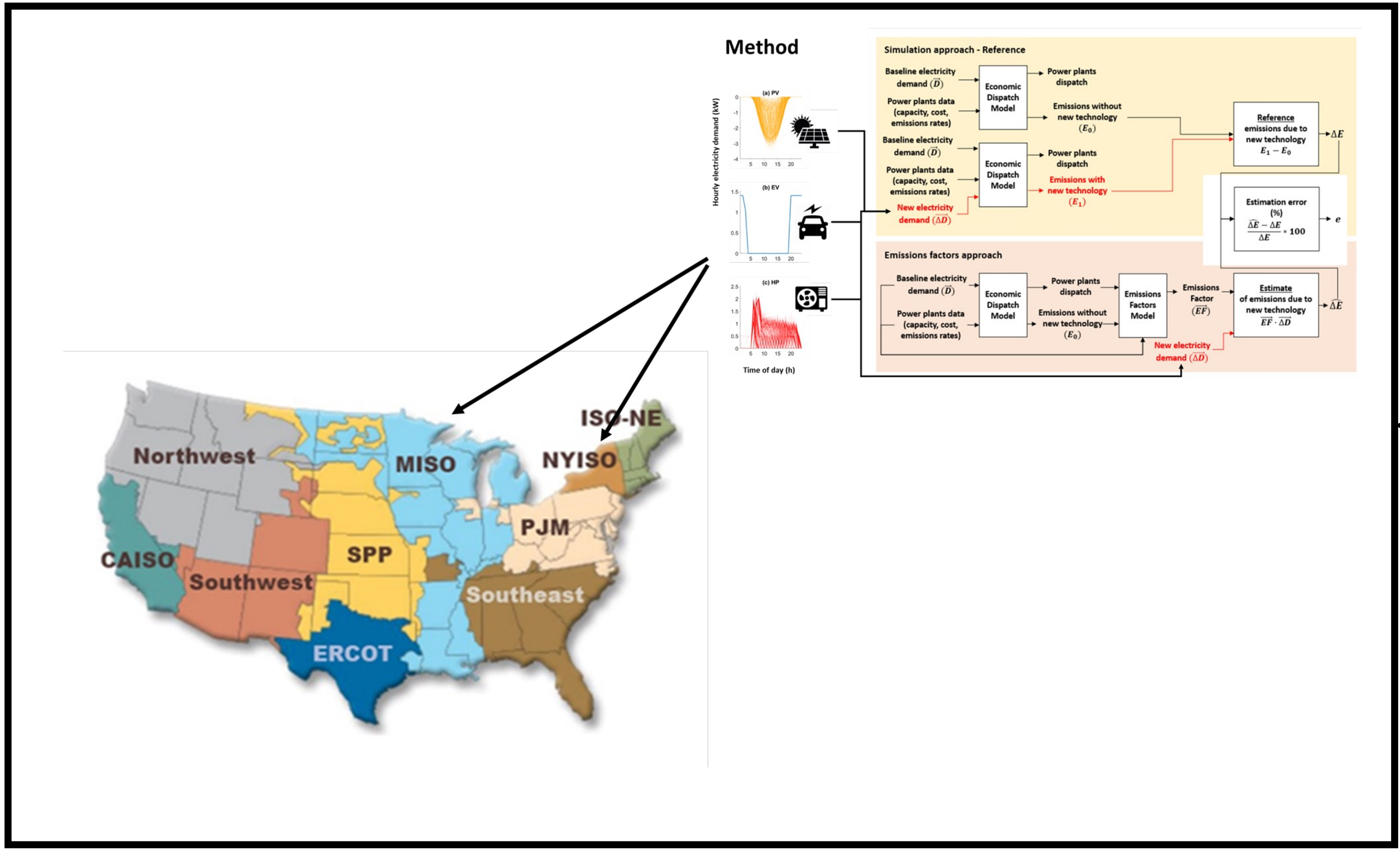


I do this for 2 grids
MISO (heavy coal)
NYISO (nuclear, hydro)



I do this for
4 temporal resolutions

Temporal resolution	Data dimensions
Hourly	Vector with 8760 elements
Season average 24-hour (24SA)	4 vectors (1 per season) with 24 elements each
Year average 24-hour (24YA)	1 vector with 24 elements
Year average (YA)	1 value

Results

Table 2. Percent difference of estimates with respect to the dispatch model reference, for all Emissions Factor methods and temporal resolutions; numbers averaged over the three technologies and two grids evaluated.; results for the base case scenario.

Estimation method	Temporal resolution				
	Hourly (%)	24SA (%)	24AA (%)	AA (%)	**All** (%)
Incremental MEF	6.0	6.1	5.9	6.6	**6.1**
Costliest MEF	6.3	6.4	6.2	2.2	**5.3**
Thermal MEF	14.8	1.8	1.1	3.2	**5.2**
Demand MEF	209	6.1	8.4	2.6	**56.5**
AEF	53.4	53.3	52.9	54.1	**53.4**
All	**57.9**	**14.7**	**14.9**	**13.7**	**25.3**

For temporal resolutions: Hourly refers to 8760 factors, one per hour of the year; 24SA to four 24-hour days representative of the seasons; 24AA to one 24-hour day representative of the year; and AA to a single value representative of the year. MEF = Marginal Emissions Factors. AEF = Average Emissions Factors.

Average Emissions Factors consistently deviate more from dispatch model results than Marginal Emissions Factors.

Annually averaged MEF are easy to use and gate the smallest differences.

Demand and thermal MEF yield much larger differences when used with 8760-hour resolution.

Excepting the 8760-hour resolution, all marginal methods performed similarly, with differences from dispatch model of <9%.

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Estimation differences are consistent between the two electricity grids.

Findings are robust to varying modeling complexity and larger demand changes.

Do Emissions Factors accurately estimate the change in carbon emissions due to changes in demand in a simulated grid?

- Estimates from five MEF methods give <10% difference from dispatch
- AEF estimates give around 50% difference
- Marginal are preferable to Average
- Regressiosn methods are problematic for hourly resolution